Fabrication and Testing of Z-Expandable Auxetic Textile Structures for Impact Protection

A Thesis
SUBMITTED TO THE FACULTY OF
UNIVERSITY OF MINNESOTA
BY

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IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF
MASTER OF SCIENCE

Dr. Lucy Dunne

September, 2015

Acknowledgements

First and foremost, I place my acknowledgements to the Almighty, the guiding force that helped me endure through the highs and lows of this endeavor. I would like to express my gratitude to the following people and institutions that have helped me with the pursuit of my thesis.

People

Dr. Lucy Dunne, for being my mentor, role model, for her honest feedback and for bringing out the best in me, by constantly challenging me to push the envelope.

Dr. Karen LaBat for her support, encouragement and updates on auxetics.

Dr. Elizabeth Bye, for serving on my thesis committee and for her valuable feedback.

Dr. William Durfee, for serving on my thesis committee and for his valuable feedback.

Dr. Julianna Abel, for her interest in the topic and for her presence during my defense.

Malathy Ramaswamy, for her undying optimism, encouragement and understanding.

Ramaswamy Ananthakrishnan, for his support and faith in my abilities.

Arvind Shankar, for his loving support, open-mindedness and out-of-the-box thinking.

Sankaran Seshadri, Uma Sankaran and Ahilesh Shankar, for their patience and understanding.

Lakshman Sankaran for his timely support and insights on mechanical engineering.

Institutions

Wearable Technology Lab- University of Minnesota-Twin Cities, for the Instron

American Standards for Testing of Materials (ASTM), for funding a part of this project

Techtextil North America 2015, for providing a platform to present a project poster

Abstract

Auxetics are counter-intuitive smart materials that grow in dimensions, perpendicular to the applied force. These materials are often used in functional clothing design, particularly for impact protection and shock absorption (Liu, Y., & Hu, H., 2010). When tensile stress is applied to conventional materials, they become narrower by pushing towards the line of stress, whereas auxetics grow in dimensions by pushing away from the line of stress. When subjected to compressive stress, conventional materials become wider by pushing away from the point of impact, while most auxetics push towards the point of impact. Since the ratio of the transverse to longitudinal strains (Poisson's ratio) for auxetic materials is negative, these are also referred to as Negative Poisson's Ratio (NPR) materials.

The manufacture of 2D and 3D auxetics is generally complex (Mslija, A., &. Lantada, D. A., 2014). Both 2D and 3D auxetics grow perpendicular to the axis that is stretched, with the difference being that 2D auxetics grow along the same plane, while 3D auxetics grow in one or more directions. (Elipe, J.C.A et. al., 2012). Limited research has been directed towards the creation and testing of 2D to 3D transformable auxetics, based on buckling, twisting and pop-up mechanisms. In this study, three Z-expandable auxetic structures were manufactured from a sheet-like textile material, compared and analyzed. The stresses that come into play during growth and recovery were identified during tensile testing. A negative Poisson's ratio for each confirmed *auxeticity* and results reveal that these structures are anisotropic. The structural parameters associated with the three prototypes were identified and analyzed.

Table of Contents

List of Tables

List of Figures

CHAPTER 1: BACKGROUND

Auxetic materials exhibit an unusual property of growing thicker when stretched and there is an increased interest towards using these materials for protective and support applications, particularly in sportswear (Shishoo, R., 2005). This section provides an overview of some terminology related to impact protection, classification of auxetic materials, Poisson's ratio, production and properties of auxetic textiles.

1.1 Impact Protection

Impact biomechanics is the study of impact forces and its effects on living systems. The prefix *bio* refers to a living system and the root word *mechanics*, refers to the analysis of impact forces and its effects in this context. (McGinnis, P.M., 2013).

In essence, an 'impact' is a result of collision of two bodies. The *impact force* is the amount of force that acts upon an object and the *time of impact* is the time taken to experience the impact force. The impact force is related to the speed and size of the colliding bodies. The shock that results from the impact gets transferred to the impacted bodies as energy. The application of impact forces results in tension, shear and compression (Watkins, S.M., & Dunne, L.E., 2015). The role of impact protective equipment is to reduce the initial force, or to safely eliminate the energy by absorbing and spreading it over a wide area. In order to minimize impact force, it is important to extend the time of collision. For instance, gymnasts land on padded surfaces to increase the time of impact during their landings, and it is for the same reason that high jumpers land on soft landing pads. These are made from cushioned materials that reduce the average impact forces by prolonging the collision time and ensure safe landing (Laing, R. M., & Carr, D. J., 2005).

According to the basic health and safety requirements defined by the European Commission, Personal Protective Equipment (PPE) for mechanical impact is expected to offer protection from falling or projecting objects and collision of parts of the body with an obstacle. PPE for mechanical impact could also protect from falls that could result from slipping and from heights, as well as mechanical vibration. Other related categories include protection against static compression of one or more body parts and protection against physical injuries such as abrasion, perforation, cuts or bites. The levels and classes of protection offered by PPEs are determined by the end application. (Scott, R.A., 2005).

1.2 Classification of Auxetics

The word *Auxetics* has been derived from the Greek word *Auxetikos* meaning 'that which tends to increase.' These materials exist in various forms ranging from the microscopic to macroscopic as shown in the classification chart below (Figure 1).

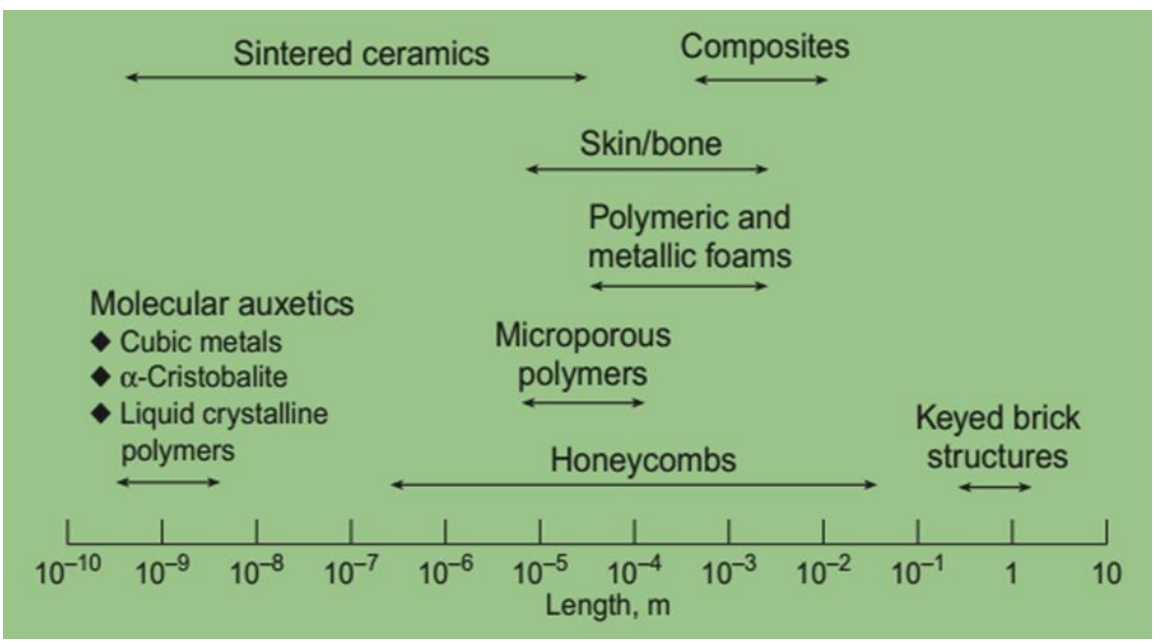


Figure 1: Classification of Auxetics (Scott et al, 2000)

Auxetic biomaterials include a number of skin tissues, soft tissues and some forms of bones. It has been reported that cat skin, cow teat skin, nuclei of embryonic stem cells and the human Achilles tendon show cross-sectional expansion when stretched and cross-sectional contraction when compressed. Interestingly, the nuclei of embryonic stem cells exhibit auxetic properties during its transformational stages of becoming a tissue-specific cell (such as that of the heart). It has been speculated that these cells would have evolved to exhibit auxeticity in order to enable 'super absorption' of essential molecules from the surrounding cytoplasm during the process of cell development. Among naturally occurring molecular auxetics, arsenic, cadmium, silicates, zeolites as well as natural crystalline cellulose are some examples (Iyer, S., 2014 & Pirolini, A., 2014).

Aside from the naturally occurring auxetics, there are several man-made auxetic materials such as the keyed-brick structure (Figure 2), re-entrant honeycombs, microporous polymers and certain forms of compressed foam.

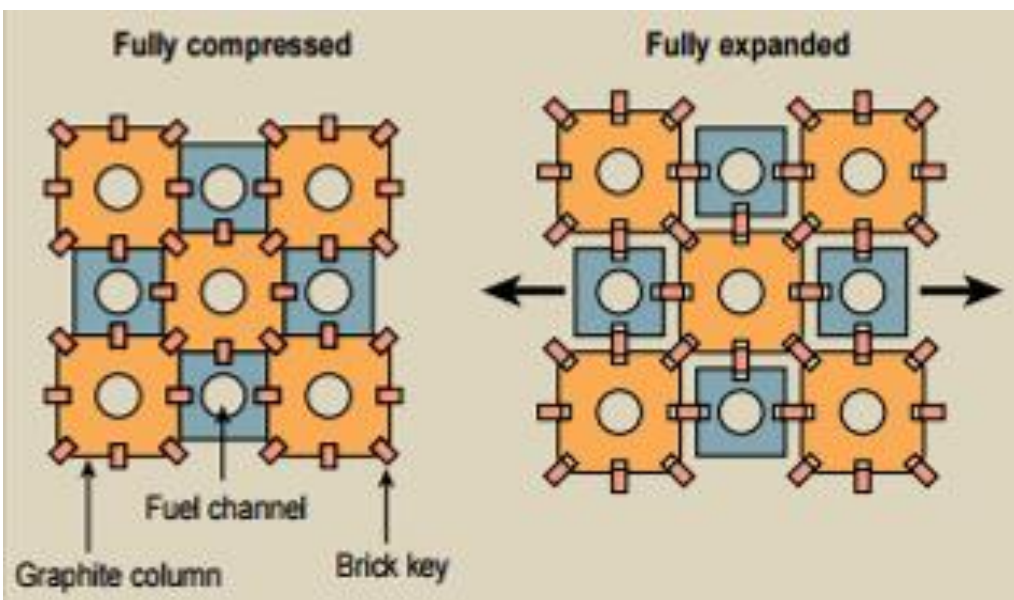


Figure 2: Macroscopic keyed brick auxetic structure that expands in all radial directions when subjected to tensile load (Alderson, A., 1999)

Some of these are created by manipulating polymers to induce the auxetic structure and properties, while some others are built molecule by molecule. In either case, the idea is to create a repeating pattern with hinges as appropriate to the structure.

In 1987, Rod Lakes synthesized a polymer-based auxetic material by subjecting polyurethane foam to triaxial compression and heat, which resulted in the buckling of the side walls of hexagonal cells. In 1988, Ken Evans fabricated another auxetic structure in PTFE, with oval nodules connected with the help of fibrils or long strands. In its relaxed position, the nodules overlapped with the fibrils. However, when stretched, the fibrils pulled taut and nodules rotated to exhibit auxeticity as shown in Figure 3(i) (Aston, D., 2010).

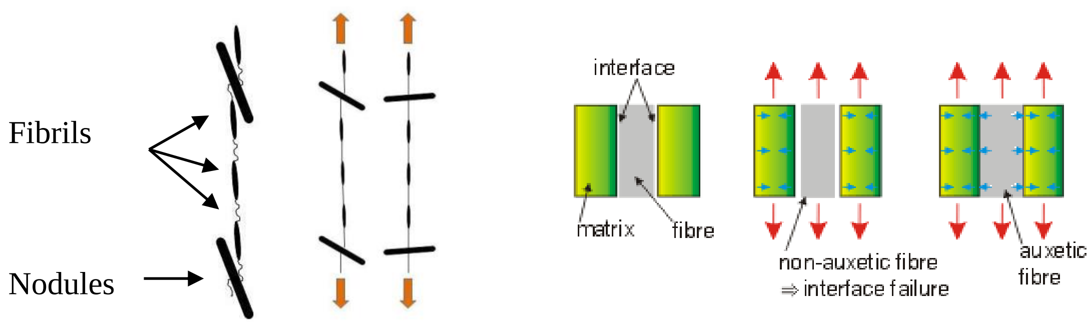


Figure 3 (i) Auxetic with fibrils & nodules (ii) Auxetic Fiber reinforced composite

Figure 3 (ii) illustrates an advantage of incorporating auxetics in composites. Composites possess superior properties because they are often made from two or more different components. In conventional fiber reinforced composites, fiber pull-out during tensile loading could result in failure at the fiber/matrix interface. This occurs due to the lateral contraction of the fiber and matrix. However, an auxetic fiber reinforced composite prevents fiber pull-out by laterally expanding during tensile loading and minimizes the failure of the composite. (Alderson, K., et. al., 2005).

Another way to classify auxetics would be on the basis of 2-dimensional and 3-dimensional structures. A vast majority of manufactured auxetics are 2-dimensional planar structures that increase in dimensions along the same plane when stretched (Lee, J.H, 2012).

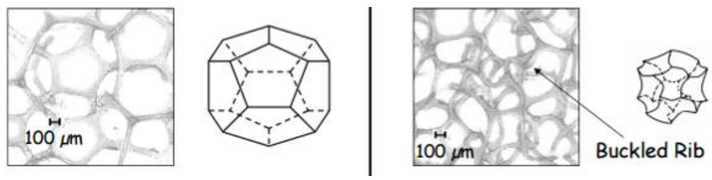


Figure 4: Foam (i) non-auxetic (ii) auxetic (Evans, 1994; McDonald, S., n.d.)

The early investigations of Rod Lakes in 1987 on auxetic foams provided a lead into 3D auxetics, specifically related to foam structures. Figure 4 (a) is a unit cell of a foam where the conventional hexagonal dodecahedron which shows positive Poisson's ratio in its 'non-re-entrant' form and negative Poisson's ratio in its 're-entrant form' (Evans, et. al., 1994). The word *re-entrant* refers to an inward pointing angle. This model is often used to understand the behavior of auxetic foams in which tensile expansion leads to lateral expansion and axial compression leads to lateral contraction (Liu, Y. & Hu, H, 2010).

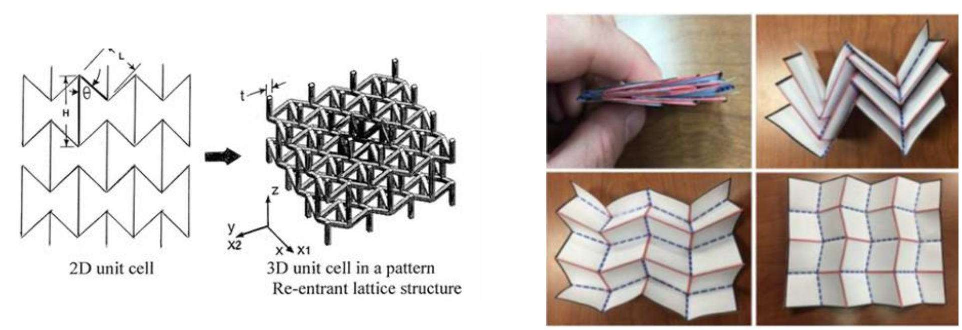


Figure 5: Auxetics (i) 3D (Yan, L., et al., 2011) (ii) Origami (Silverberg, J.L., 2014)

Recent advances in 3D auxetics have been possible through computer aided design (Elipe, J.C.A, et al., 2012) and additive manufacturing techniques such as 3D printing (Abdelaal, O.A, et al., 2012) and through techniques such as Origami (Silverberg, J.L., 2014). Figure 5(ii) shows an eggrack auxetic. The differences between 2D and 3D auxetics will be covered in subsequent sections.

1.3 Poisson's Ratio and Auxeticity

When a tensile force is applied to a unit area of a material (also known as stress), in proportion to the stress, the material tends to elongate in the direction of application of force (axial direction) and becomes narrower in a direction perpendicular to the force (transverse direction). Broadly speaking, stresses may be tensile, compressive or shear in nature.

The ratio of the difference in length to the original length is known as strain. Strain can be tensile or compressive in nature. Tensile strains are assigned a positive sign because they are generally expected to elongate the material, while compressive strains are assigned a negative sign because they are generally expected to shorten the material. Usually, when the axial strain is tensile (+ve), the transverse strain is compressive (-ve) and if the axial strain is compressive (-ve), the transverse strain is tensile (+ve). Since Poisson's ratio is a negative ratio of the transverse strain to the axial strain, conventional materials have a positive Poisson's ratio. However, in the case of auxetic materials, when the axial strain is tensile (+ve), the transverse strain is also tensile (+ve), resulting in a negative Poisson's ratio (Grima, N. J, 2010).

$$\text{Engineering Poisson's Ratio} \quad = \quad \text{- ve of} \left(\frac{\text{Strain}_{\text{Transverse}}}{\text{Strain}_{\text{Axial}}} \right)$$

In Figures 6(i) and 6(ii), the non-deformed object is indicated with a solid line and the deformed object (after loading) is indicated with a dashed line.

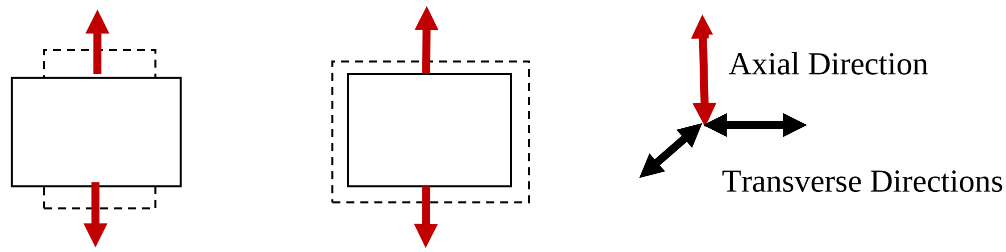


Figure 6: Tensile loading in (i) conventional (ii) auxetic materials

Poisson's ratio depends on the shape of the rigid unit, degree of aperture, connectivity, extent of rigidity of the unit. Auxetic behavior is induced by the internal geometry and the deformation mechanism of the structure. As is evident from the range of naturally occurring and manmade auxetics cited in the previous section, the negative Poisson's ratio is a scale- independent property. In other words, it can manifest at the microscopic and macroscopic levels (Grima, N. J, 2010).

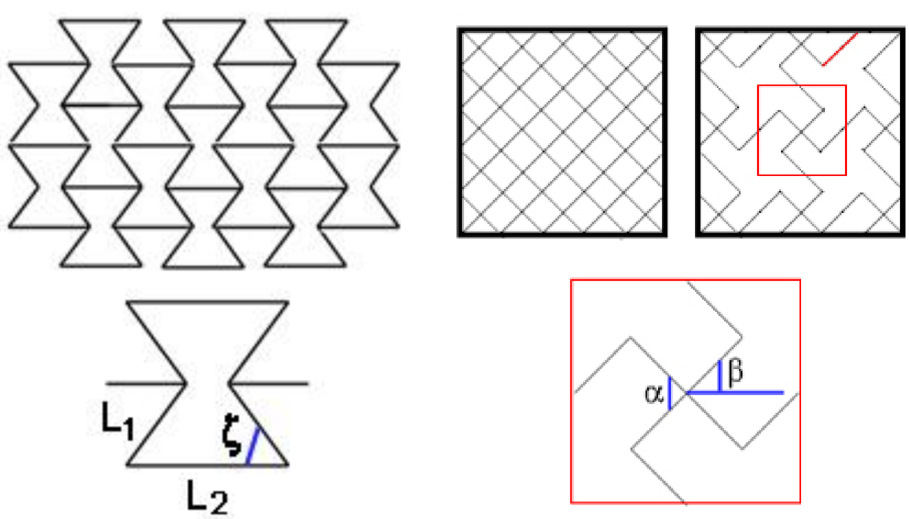


Figure 7: (i) Re-entrant honeycomb (ii) missing rib auxetics (Freiberger, M., 2011)

The re-entrant honeycomb and missing rib auxetic structures illustrate how the shape of pores can influence the Poisson's ratio. Square, circular and hexagon shaped pores give a positive Poisson's ratio. Figure 7 (i) depicts the re-entrant honeycomb structure which is one of the most commonly cited examples in the literature on auxetics. The Poisson's ratio of this structure depends upon lengths L_1, L_2 and the angle ζ. Figure 5 (ii) represents the missing rib structure which is formed by removing sides from a quadrilateral lattice. The Poisson's ratio for this structure depends upon the angles α and β (Freiberger, M., 2011).

Studies show that rubber that is manufactured with a positive Poisson's ratio results in a material that is amenable to shear deformation, but is relatively incompressible. However, when manufactured with a Poisson's ratio of -1, the material is more amenable to compression and relatively difficult to shear. Thus, auxetics allow for volume changes while maintaining shape (Pirolini, A., 2014).

1.4 Mechanism

This section highlights some examples of deformation mechanisms observed in auxetics, to better understand the working principles and design of structures. When the arrowhead honeycomb structure (shown in Figure 8(i)) is subjected to tension, its cells open due to the bending and (or) hinging of the ribs. In the chiral honeycomb structure (Figure 8(ii)), the auxeticity is induced by the flexing of the ligaments due to the rotating cylinders (Sanami, M., et al., 2014).

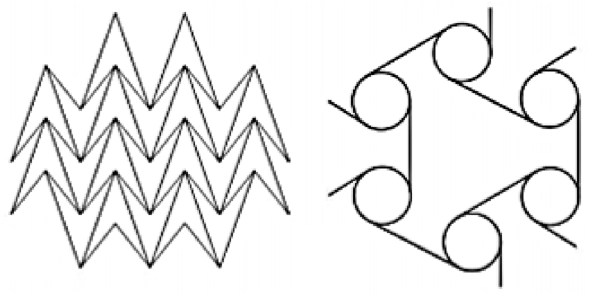


Figure 8: (i) Arrowhead honeycomb (left) (ii) Chiral Honeycomb (right) (Sanami, M., et al., 2014)

Blumenfeld and Edwards (2012) defined auxetic behavior on the basis of building blocks called '*auxetons*,' which expand and rotate with application of force from three '*contact points*.'

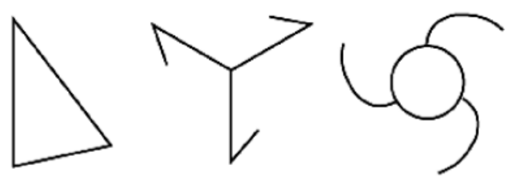
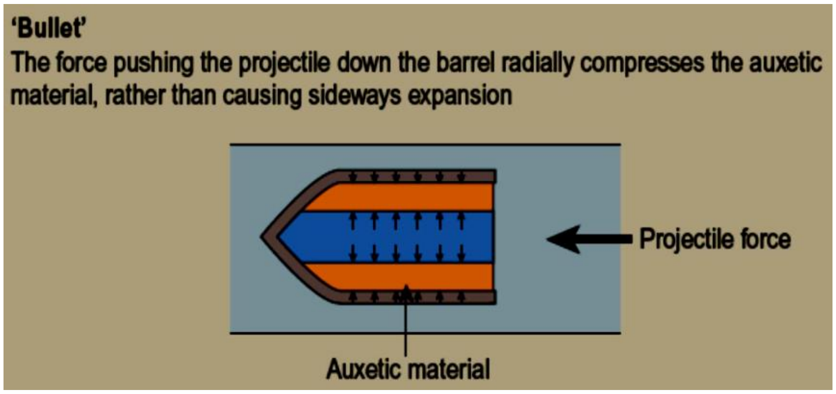


Figure 9: Auxetons with three contact points

In 2009, Alderson and Evans identified that rotation and dilation are two mechanisms that lead to auxeticity in tetrahedrons such as α-quartz and α-cristobalite 3D structures. Buckling has also been identified as a mechanism for inducing auxeticity in 3D structures (Babaee, S, et al., 2013).

1.5 Scope and Application of Auxetics in Technical Textiles

Auxetic polymeric materials are often used in combination with other materials for personal protective sportswear such as crash helmets, knee pads, shin pads, ballistic protection and gloves due to their ability to absorb energy (Liu, et al, 2010). The Defense Clothing and Textile Agency (DCTA) in Colchester has been looking at applications of auxetic textiles for military purposes as shown in Figure 10 (i) (Liu, 2006).



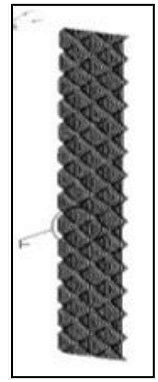


Figure 10: (i) Auxetics for Ballistics (Alderson, 1999)-Image to the left (ii) Auxetic vehicle safety belt braid (Dalian University of Technology, 2012)-Image to the right

Another critical application which can deploy auxetics is that of seat belts which can increase the time of impact and minimize injury to passengers by spreading the impact force over a wider area (Underhill, R., 2014). The vehicle safety belt braid is an auxetic braided structure shown in Figure 10(ii), having 'pull expansion units' which increase contact area of the belt and human body during the time of impact (Dalian University of Technology, 2012).

Auxetics are suitable for fitting the human body (Figure 11).Since these materials curve in the same direction of the bending force (Lakes, 1987; Evans, 1990; Cherfas, 1990), it would enhance conformability while offering impact protection, making it suitable for incorporation into clothing systems. Because of its relatively low stiffness, auxetic yarns and fabrics find applications in compression hosiery and support garments. Auxetic foam inserts are often used in intimate apparel for enhanced support, comfort and fit (Wright, J.R., et al., 2012).

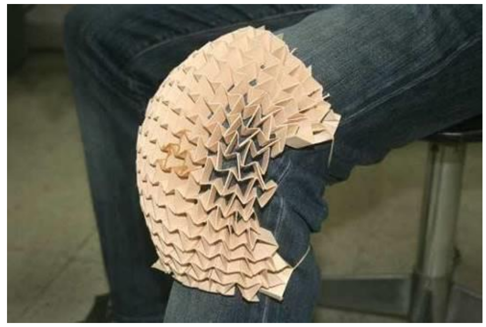


Figure 11: Conformability of auxetics (Times of Malta, 2009)

Since auxetics have the ability to open out and increase in porosity under tension, these structures can be used in applications requiring enhanced air permeability when stretched. (Wang, et. al., 2013). Figure 12 shows an application where an auxetic bandage can be used for controlled drug release of anti-inflammatory, anti-odor or anti-bacterial medication that has been impregnated into the material (Alderson & Alderson, 2005).

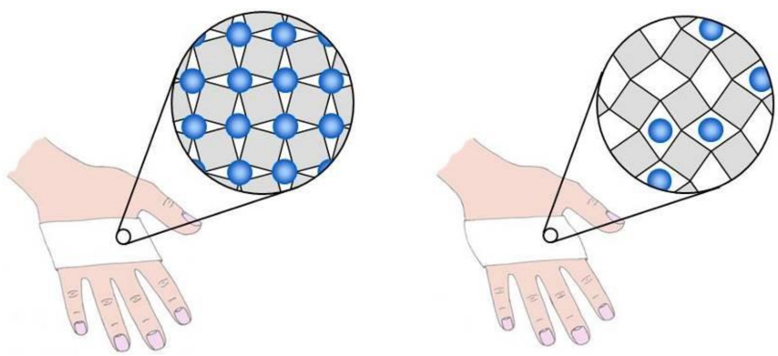


Figure 12: Auxetic Smart Bandages (Alderson & Alderson, 2005)

1.6 Production of Auxetic Textiles

There are multiple routes to manufacturing 2D and 3D auxetic textiles, as shown in Figure 13. Inherently auxetic textile fibers could be used to make a fabric that exhibits auxetic behavior. Alternatively, conventional fibers could be made into an auxetic structure as well (Alderson et. al., 2012).

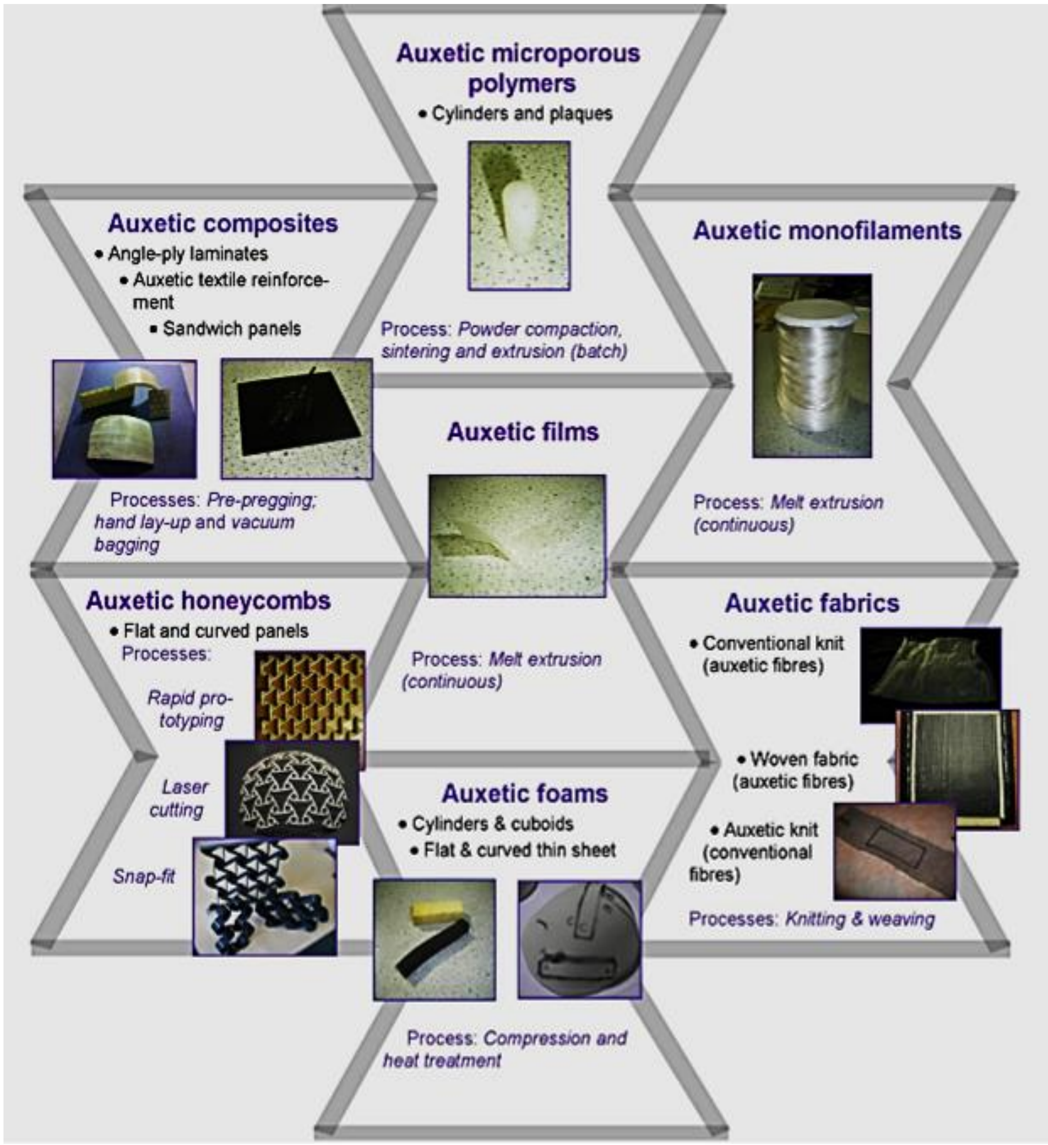


Figure 13: Production of Auxetics (Alderson, A., n.d.)

Hook proposed the Helical Auxetic Yarn (HAY) structure, made by helically wrapping a stiff filament yarn around a thicker compliant core yarn. When subjected to tensile stress, the stiff filament yarns tend to straighten out, causing the core to buckle, as shown in Figure 14 (Hook, P., 2011 & Rant et al., 2013).

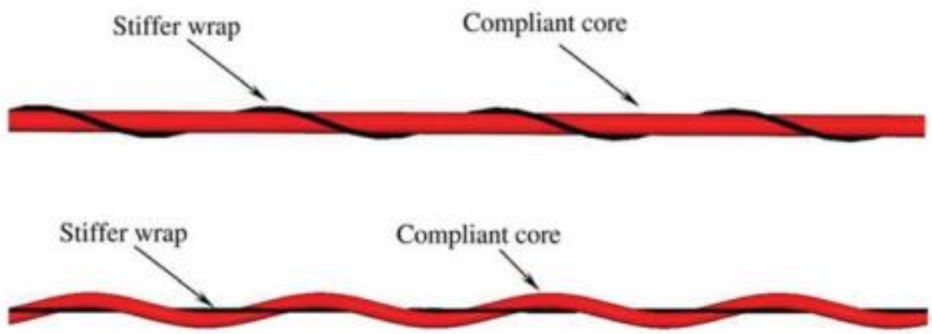


Figure 14: Helical Auxetic Yarn (Rant et al., 2013)

In a recent research study, ‘rotating square’ auxetic structures (Figures 15(a) and 15(b)) with enhanced mechanical properties were designed and manufactured for the application of stents for palliative treatment of esophageal cancer. Polyurethane foam sheets were laser cut to the desired structures using the CNC guided laser cutter and the compressive stress-strain behavior was tested on the Instron. Employing the auxetic cell geometry improved the stenting outcomes. The material could get wider when stretched, offer stiffness without being brittle and minimize stresses (Bhullar S.K., et al., 2013). While these were tested in 2D, the final product was made by rolling these flat sheets into tubular cylindrical shaped stents.

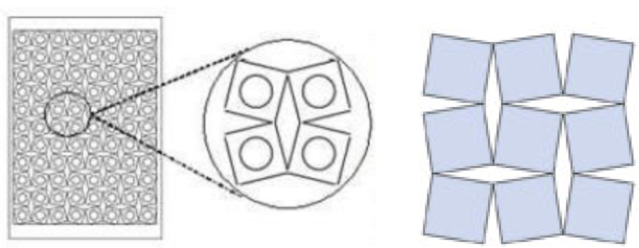


Figure 15: (a) Rotating Square Auxetics without holes (left) and (b) with holes (right) (Bhullar S.K., et al., 2013)

In the recent past, there has been a propensity towards developing 3D auxetic textiles. Most attempts to create 3D auxetics involve stacking layers of 2D auxetic planar structures which could be achieved through knitting, 3D weaving (Figure 16) or 3D printing. An example of each has been discussed in the following section.

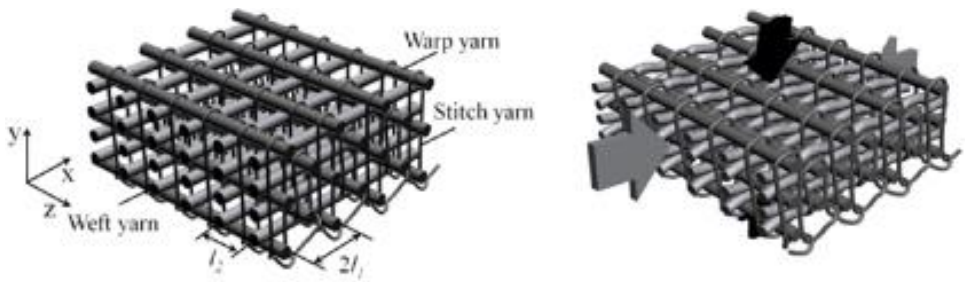


Figure 16: 3D weaving mechanism

A recent study employed various warp knit 3D spacer auxetic fabrics (Figure 17), formed by connecting two face layers of 2D auxetic structures made from parallelograms with spacer yarns forming the middle layers which showed growth along all directions when stretched. The highest auxetic behavior was examined when stretched in the weft direction and the lowest was observed in warp direction. The auxetic behavior also reduced with increase in tensile strain. It was also revealed that the auxetic fabric will retain 65% of its effect after 10 cycles of extension. This property makes it useful for sports and protective applications. Another advantage is that these are washable and may be cut to desired dimensions (Wang et al., 2013).

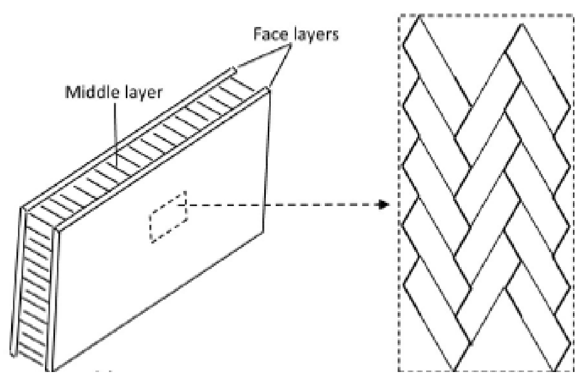


Figure 17: 3D Spacer Auxetic Fabric with Parallelograms (Wang, et al., 2013)

Oluwaseyi Sosanya created 3D auxetics (Figure 18) using a 3D loom that layers thread (made from cotton, paper and wool) from the x, y and z axes, following which the 3D fabric undergoes a post-production silicone treatment to maintain the structural integrity (Rafer, A., 2014).

Figure 18: 3D auxetic incorporated in a shoe sole (Rafer, A., 2014)

As part of a larger study, Martha Glazzard created a 3D printed structure from a rubber that demonstrated auxeticity along the Z-axis when pulled along the Y-axis (Glazzard, M, 2014).

Figure 19: 3D printed z-expandable auxetic (Glazzard, M., 2014)

CHAPTER 2: PRE-RESEARCH

2.1 Rationale for Research

It is significant to note that compared to auxetic fibers and auxetic yarns, studies related to auxetic fabrics and sheet structures are limited (Wang et.al, 2013). Further, the manufacture of 2D and 3D auxetics is generally complex (Mslija, A., &. Lantada, D. A., 2014). Based on the literature reviewed so far, it can be understood that planar 2D auxetics exhibit growth in a direction perpendicular to the axis that is subjected to stretch along the same plane. In other words, there is a *change in area* in the case of 2D auxetics. For instance, auxetics designed in the XY plane, experience growth along the X direction when stretched along the Y axis. 3D auxetics on the other hand, may grow in one or more directions perpendicular to the axis of stretch. For instance, when a 3D auxetic is stretched along the Y direction, it is possible for a 3D auxetic to experience growth only along the Z direction, or simultaneously along the Z and X axes. Therefore, in the case of 3D auxetics, there is a *change in volume* (Elipe, J.C.A et. al., 2012).

Although there are separate studies on 2D and 3D auxetics, there is limited research directed towards easily manufacturable auxetic textile structures that transform from 2D to 3D and demonstrate growth along the Z–direction, for incorporation in an impact protective clothing system.

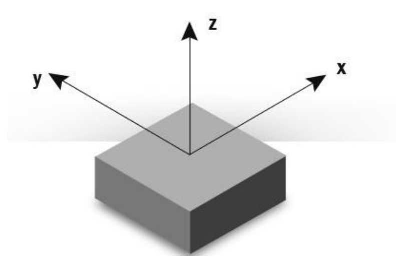


Figure 20: x, y and z axes

This study provides an approach to identifying and validating mechanisms that facilitate auxetic action. This research focuses mainly on tensile behavior, while acknowledging that the analysis of compressive behavior would complement the results obtained.

For the purposes of this study, it is assumed that a 2D structure is less than or equal to 0.25 inches in thickness. In impact protective clothing applications, using a single sheet of 2D auxetic would enable change in area along the same plane, and lack the capability to expand along the Z-direction. If a 3D auxetic were to be used instead, although it would have the capability to expand along the Z-direction, it is likely to constitute a fairly bulky structure to begin with. However, this research demonstrates that the best of both worlds could be achieved with the use of transformable auxetics with dramatic Poisson's ratios, that not only offer the structural flatness similar to that of a 2D auxetic in relaxed position, but also the capability to expand along the Z-direction and bulkiness of a 3D auxetic when subjected to a stress along the Y-direction.

2.2 Research Questions

The research questions associated with this study are as follows:

(i) Is it possible to create auxetics that transform from 2 dimensional thin structures to 3 dimensional structures, thereby demonstrating growth along the Z-axis?

(ii) If yes, what are the associated mechanisms that drive the Z-directional growth, and how does the transformation take place geometrically?

(iii) How can the transformation be characterized?

2.3 Prerequisites

In order to seek responses to the previously stated research questions, the behavior of the Z-transformable auxetics should:

(i) Demonstrate growth in the Z direction (normal to the plane), when subjected to stress along the Y axis, thereby transforming from 2D to 3D and to identify mechanisms. The mechanism associated with every Z-expandable structure can be categorized into three stages. Stresses that come into action when the prototype

  a. Is stretched along the Y axis

  b. Grows along the Z-axis to become a 3D structure

  c. Recovers to become a flat planar 2D structure.

(ii) Return to their original configuration as soon as the stresses that they are subjected to are removed. In other words, the deformation that these structures undergo would be elastic, and not permanent. The growth along Z-direction is retained only as long as the structure is subjected to a stress in the tensile direction (along the Y axis).

(iii) Be easily fabricable from a sheet-type textile material such foam and (or) fabric.

2.4 Ideation

Divergent thinking is usually indexed by fluency, flexibility, and originality of mental operations (Csikszentmihalyi, 2001). The mind map shown in Figure 21 is an example of divergent thinking. The next phase of divergent thinking in this research, involved the creation of multiple prototypes. Convergent thinking is the ability to select the best alternatives (Csikszentmihalyi, 1996). In this study, clustering of ideas can be considered as a form of convergent thinking. During ideation, an attempt was made to reserve judgment and fear while brainstorming. Ideation was unstructured to begin with, and more structured towards the end.

Figure 21: Mind map showing scope for innovation in Auxetics

Paper prototypes were created during the preliminary stages of the research. These initial structures were useful in experimenting with the direction of stretch and in identifying mechanisms, as shown in Figure 22. The herringbone structure was modelled after the Wang et al, study (2013). Slits were cut into the basic 2D herringbone structure to achieve buckling action along the Z-direction. The herringbone structure grew vertically when pulled along the diagonal. The wave and arc structures were generated based on open ideation, using pop-up card mechanisms as inspiration. These grew vertically when pulled along the diagonal and vertical directions.

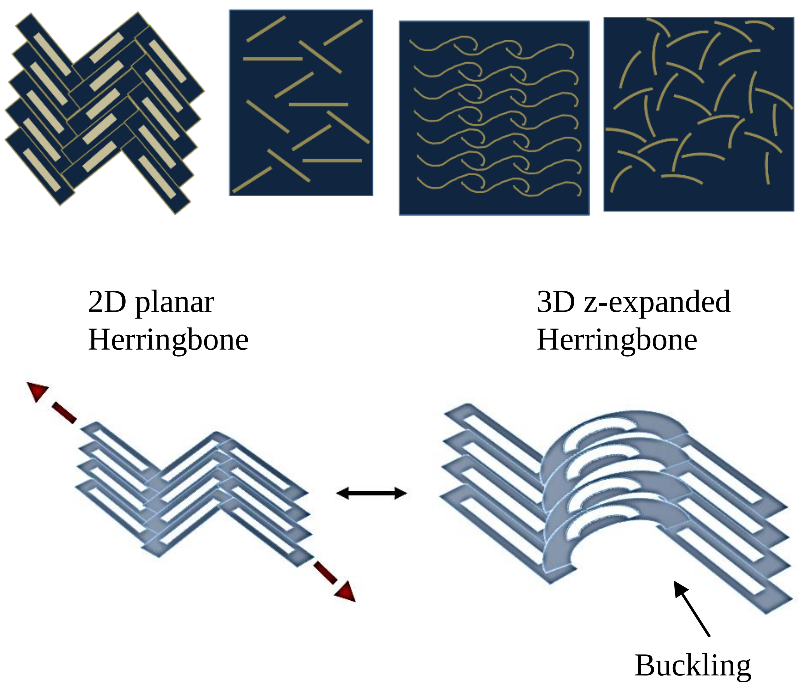


Figure 22: Paper Prototypes (i) Herringbone (ii) Wave and Arc (iii) Herringbone mechanism

It was also realized that the inherent properties of the material used for prototyping, such as the stiffness or resistance of paper and the extensibility of foam could impact the performance of these prototypes. Several iterations of prototyping was done for the Pleat pop-up and Buckling Triangles prototype. These have been discussed in the subsequent section.

2.5 Z-Expandable Pleat pop-up: Basic Mechanism

‘Springs’ were identified as a source of inspiration for inducing Z-expansion. The mechanics of a spring (Figure 23), both in loaded condition, as well as its expansion along the Z-direction when unloaded, was interesting.

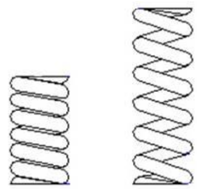
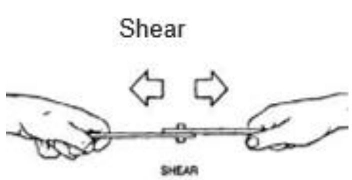
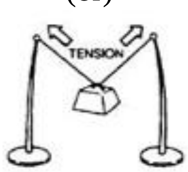


Figure 23: Compression spring- loaded and unloaded conditions (Mitcalc, n.d.)

Table 1 shows the three phases associated with the pleat pop-up mechanism, which includes a combination of torsion and radial stresses during growth, when the structure is subjected to a tensile stress, and a combination of compression and radial stresses during recovery.

<table>
<tr><th>Stresses that the structure is subjected to</th><th>Stresses that come into play during growth</th><th>Stresses that come into play during recovery</th></tr>
<tr><td>Shear or Tension

(or)
</td><td>Combination of torsion and radial stresses

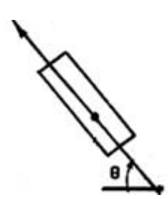
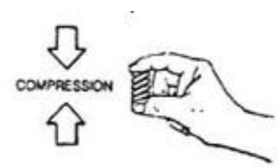
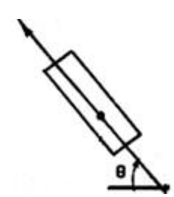
</td><td>Combination of compression and radial stresses

</td></tr>
</table>

Table 1: Stages of the Pleat Pop-up mechanism

In order to better understand the mechanics of the spring, it was initially prototyped using paper. Figure 24 shows the steps for making a paper spring using two strips of paper.

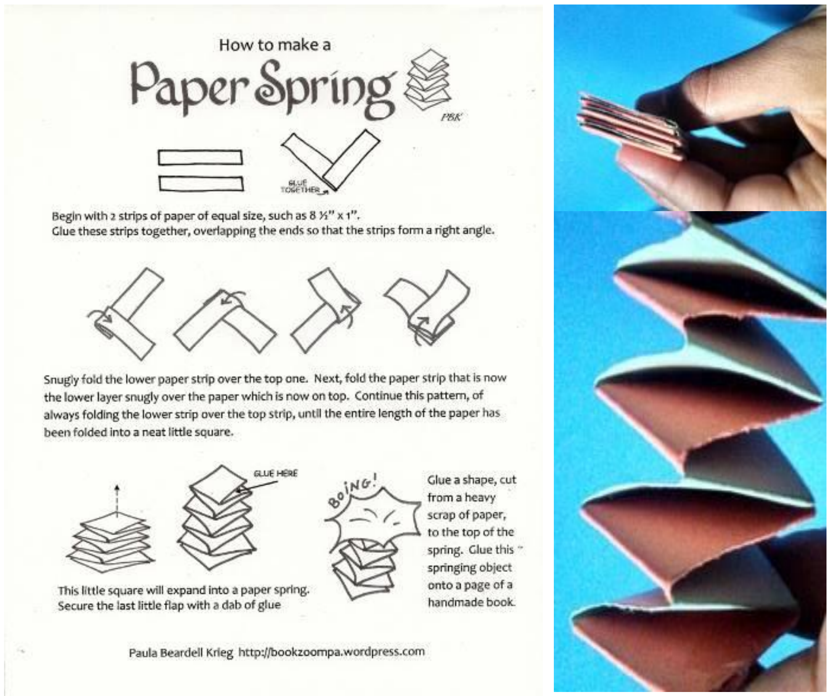


Figure 24: (i) Image to the left (Krieg, P. B., 2010)-How to make a paper spring (ii) Images to the right (Instructables, 2015)-Paper spring in action

Following this, an attempt was made to translate the action of a compression spring in a Z-expandable auxetic structure. In order to execute this, it was necessary to find a textile material that would retain folds and lie flat when compressed, and also expand three-dimensionally when subjected to a tensile stress.

Among several synthetic fabrics that were explored, it was observed that Ripstop Nylon GSM 44 would be most suitable for retaining pleats. Heat-setting was identified as a suitable manufacturing process to set permanent folds in the chosen fabric.

The ‘Oribotics Fabric Folding Process’ video (Gardiner, M., 2011) was used as a basis to understand the process of heat setting fabrics in the oven. Alternatively, this could also be done using the iron. Springs kept in the oven for heat setting were made by sandwiching a single strip of ripstop nylon with two strips of paper cut to the same dimensions. This arrangement was to prevent the spring from getting scorched from the heat. This assembly was then heat set between 149-177 degrees Celsius (Caroline, H.K. H., 2010).

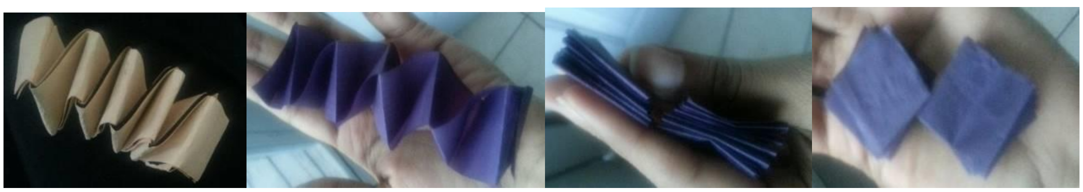


Figure 25: (from left to right): (i) Spring Assembly for heat-setting in the oven Springs from ripstop nylon GSM 44 (ii) (iii) Side Views (iv) Top View

Multiple springs were then glued onto two square sheets of ripstop nylon on the top and bottom, to create a Z-expandable structure as shown in Figure 26.

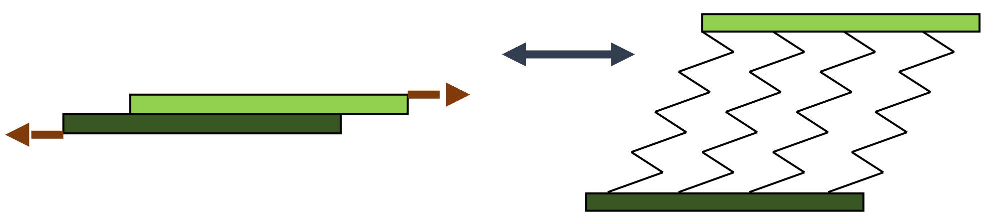


Figure 26: Basic working principle of Pleats pop-up version 1

Although the selection of materials and manufacturing methods was apt for creating a prototype that successfully demonstrated this effect, a major drawback was that it could not possibly offer crush resistance or withstand compressive loads, particularly during deformation—a feature that would be critical to auxetic structures used for impact protection. In order to overcome this problem, industrial felt and (or) foam were chosen for enhanced compression resistance and durability of the prototype.

Figure 27 shows the theoretical working principle associated with the second version. In the absence of a tensile force, the pleats would lie flat when subjected to a tensile force, the pleats would move in a radial manner and orient itself perpendicular to the horizontal.

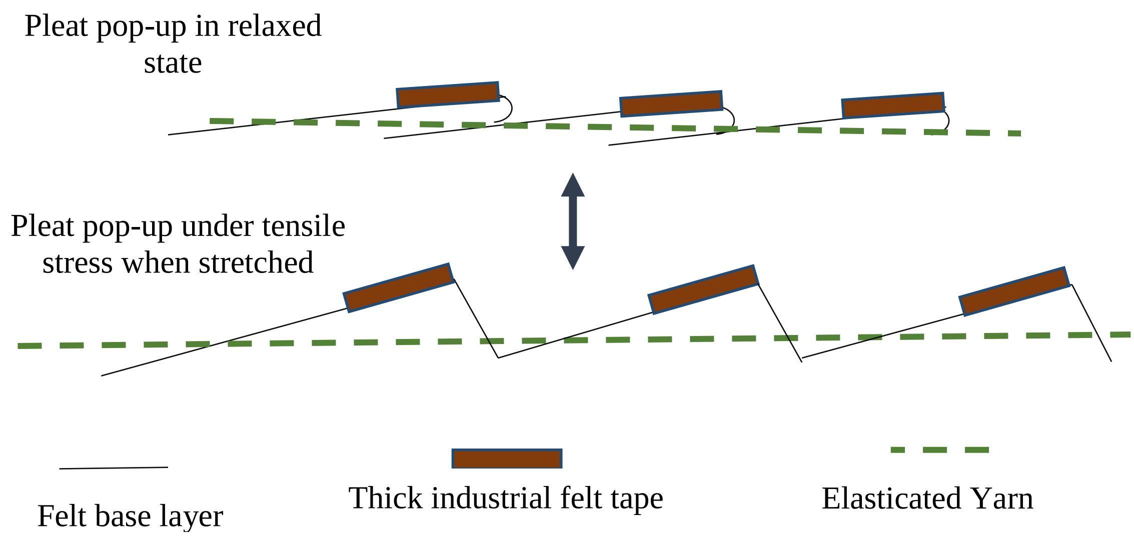


Figure 27: Basic working principle of Pleats pop-up version 2

The base layer of this prototype was made from synthetic industrial grade felt was heat-set into knife pleats using an iron (Figure 28). In order to facilitate the radial movement of pleats when subjected to a tensile force, elasticated yarn was threaded through every pleat, on the reverse side of the structure. Along the top edge of every pleat a thick industrial felt tape piece was attached with the help of super glue, as shown in Figure 29, so as to withstand compressive loads.

Figure 28: Felt fabric base layer with heat-set knife pleats

Figure 29: Z- expandable industrial felt pleated prototype (version 2)

However, some major caveats associated with this setup was that the thick industrial felt showed resistance to cooperate with the base pleats during radial action and kept collapsing under the weight of the thick felt. Therefore, in the subsequent version, a different element/mechanism that would not interfere with the radial movement of the pleats was chosen.

In creating the third version of the pleat pop-up (Figure 31), the idea of translating the mechanics of a spring into a Z-expandable structure was revisited. At the same time, it was important that the mechanisms/elements offering impact protection would not obstruct the radial movement of pleats.

A spring is essentially a coil that stretches when pulled. It gets back to its original configuration when the force is removed. In other words, it has elasticity. Previously, in version 1, a paper spring was created from two strips. A different and much simpler approach was explored this time-- a concentric shape was created by cutting along the dotted lines shown in Figure 30.

Figure 30: Spring from concentric shape (i) Template (ii) Paper (iii) Foam

Instead of using a thick industrial felt tape that precluded the free movement of pleats as in the case of Version 2, it was identified that a planar concentric piece of foam that transformed into a 3D spiral structure could be easily inserted between pleats. The working principle was that when the fabric is subjected to a tensile force, as the pleats move in a radial manner, the otherwise flat concentric foam shapes would spiral out (expand) to offer impact protection.

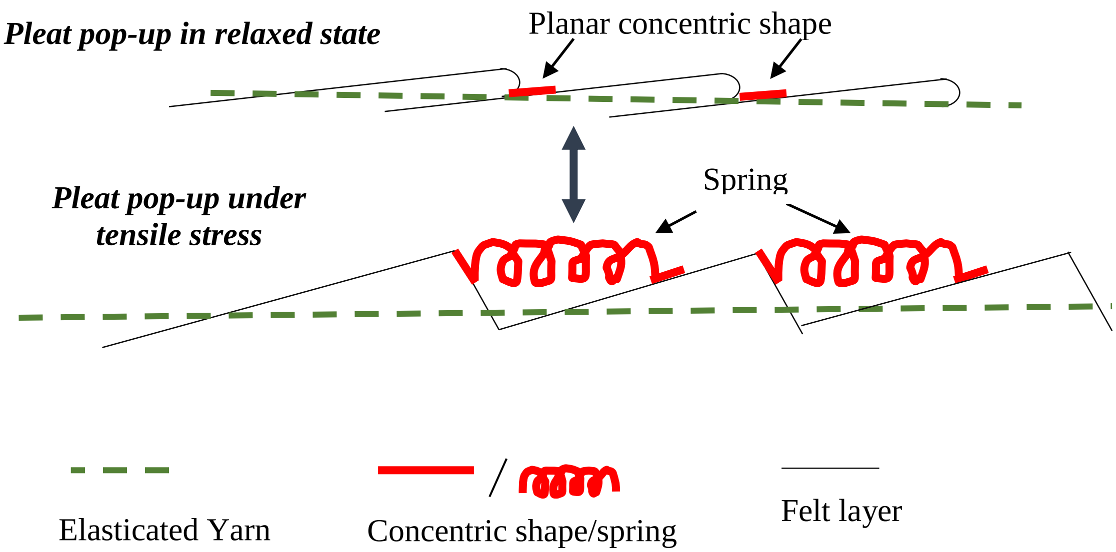


Figure 31: Basic working principle of Pleats pop-up

To start with, the pleats in the base felt fabric were heat-set in the oven and elasticated yarn was sewn through the pleats on the reverse side of the felt fabric. Subsequently, concentric spiral pieces of foam were glued between pleats (one end of the spiral to the first pleat and the other end to the next pleat). Elasticated yarn was threaded through every pleat, on the reverse side of the base fabric.

Figure 32: Pleat Pop-up Version 3 (i) in relaxed and (ii) stretched positions

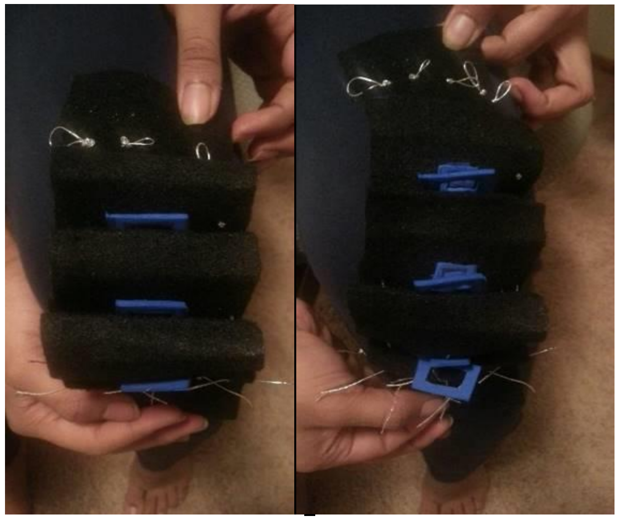


Figure 33: Pleat Pop-up Version 3 (i) Relaxed (left) (ii) Stretched (right)

Although the transformation of a 2D concentric shape to a 3D spring worked, one major problem associated with this prototype was that the pleats would not lie flat. On further analysis of the prototype, it was identified that the elasticated yarn offered excessive tension, as a result of which the pleats always stood up. In other words, the transformation was from 3D to 3D, instead of 2D to 3D. This problem was overcome in the final prototype which was considered for testing, and the details have been discussed in the subsequent chapter.

2.6 Z-Expandable Slot Pop-up: Basic Mechanism

In exploring various mechanisms that induce the auxetic effect in transformable structures, apart from buckling, the pop-up mechanism was identified as a potential area to tap into for achieving growth along the Z direction. Pop-up cards (Figure 34) follow a mechanism that enables a compressed cut out to spring up when opened or otherwise activated to a three dimensional form.

The slot pop-up described in the following section takes inspiration from pop-up cards, the opening of which demonstrates a 2D to 3D transformation.

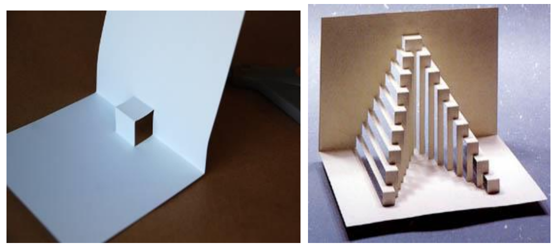


Figure 34: Pop-up Cards (Images: Tinkerlab, 2013 and Chatani, M., 2015)

The table below captures the stresses associated with the slot pop-up mechanism. When the structure is subjected to a shear stress, it undergoes radial stress induced growth and radial stress induced recovery when the shear stress is released. Since this concept was fairly straightforward, multiple design iterations were not necessary for this prototype. The design and manufacture of the final prototype has been discussed in the subsequent chapter.

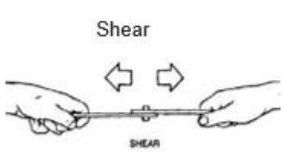
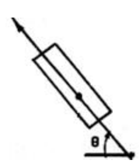
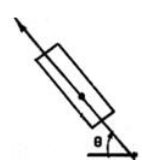
Stresses that the structure is subjected to	**Stresses that come into play during growth**	**Stresses that come into play during recovery**
Shear stress 	Radial stress 	Radial stress 

Table 2: Stages of Slot Pop-up mechanism

2.7 Z-Expandable Buckling Triangles: Basic Mechanism

Table 3 captures the stresses associated with the buckling triangles mechanism. When the structure is subjected to a tensile stress, it undergoes buckling (a combination of tension and compression) in a certain direction, and buckling occurs in the opposite direction during recovery, when the tensile stress is released.

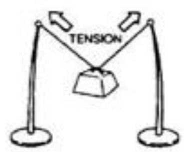
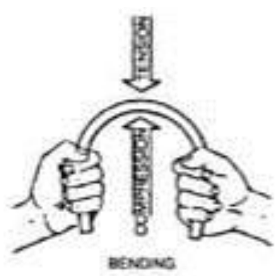
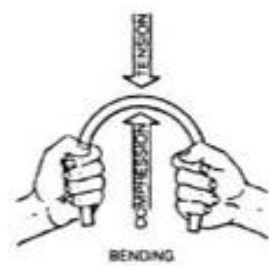
Stresses that the structure is subjected to	**Stresses that come into play during growth**	**Stresses that come into play during recovery**
Tension 	Buckling/Bending (combination of tension and compression) 	Buckling/Bending (combination of tension and compression) 

Table 3: Stages of the buckling triangles mechanism

Initially, this effect was observed in the 'star structure,' which was created from open-celled foam, as shown below in Figure 35. It was interesting to observe that this particular structure showed a similar form of vertical growth in the form of buckling on paper and foam, despite the inherent differences in material properties.

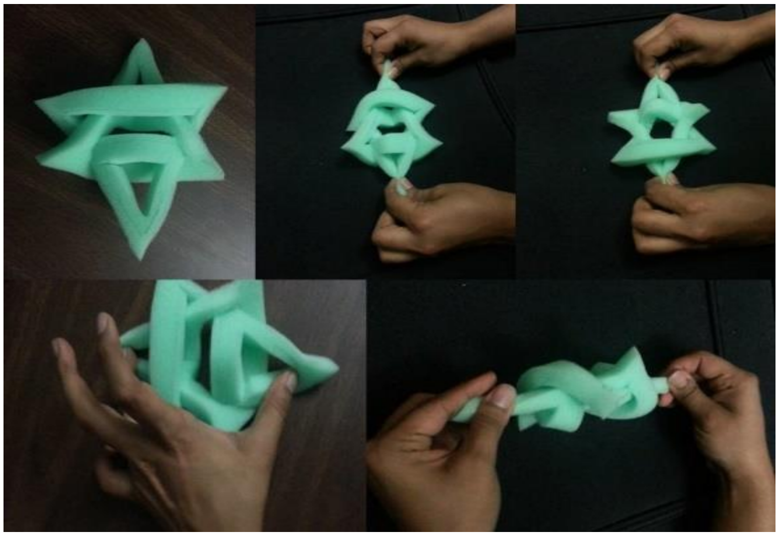


Figure 35: The Star Structure

Figure 36 shows the buckling action that takes place when the star structure is subjected to a tensile stress along the Y direction.

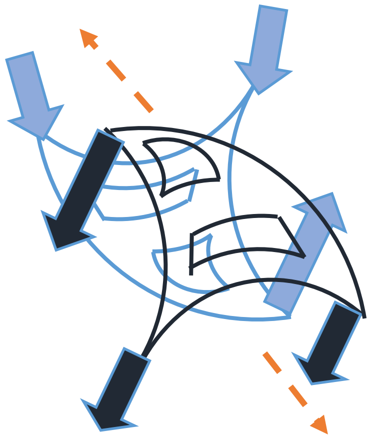


Figure 36: Star structure mechanism

Having developed this ‘star structure,’ it was necessary to investigate whether several small repeatable star units could be combined to create a larger structure for the purposes of manufacturing a sheet-like structure. To that end, four such units were combined and fastened together with strips of foam to create the structure shown in Figure 37 (i).

The second idea was to create a sheet-like structure consisting of columns of triangular units oriented in opposite directions, in an alternate fashion (with units facing downwards in one column and upwards in another, and so on), as shown in Figure 37 (ii). It was cut from a single sheet of foam.

While the first structure retained four ‘star units’ completely (i.e., a single unit was created by interlocking two triangular subunits to resemble a star), the subsequent structure used the triangular subunits separately and was not in the form of a star. When subjected to a stress along the Y-axis, neither of these demonstrated an auxetic effect along the Z direction because it could be observed that certain elements in these structures precluded volume change in the form of buckling.

In the case of the first structure, the strips of foam that held the four star units together precluded growth along the Z-direction. In the case of the second structure, only the triangles in the top left corner and bottom right corner demonstrated slight buckling. The structure did not demonstrate consistent growth by buckling throughout.

Figure 37: Buckling Triangles (i) first version (left) (ii) second version (right)

Based on the two previous structures, it could be posited that the interlocking of two triangular sub-units was necessary to induce the buckling effect. The third structure shown in Figure 38 was created by interlocking 9 triangular sub-units, with alternate columns overlapping. Similar to the second structure, the triangular units of the first column face downwards, those of the second column face upwards, those of the third face downwards, and so on, with the difference being that every triangular unit was attached with the help of a stitch. While this structure showed definitive growth along the Z-direction when subjected to a tensile force, it was observed that the buckling was rather minimal.

Figure 38: Buckling Triangles-Third Version

An attempt was made to enhance the auxetic effect by enhancing the buckling action of sub-units, so as to provide optimal growth along the Z-direction. Based on a literature review of characteristics of sub-units in auxetics, it was identified that the inherent stretch properties and lack of stiffness of open-celled foam may be precluding the structure from exhibiting auxeticity.

Close-celled foam was chosen to replace open-celled foam because it provided some level of pliability for easy buckling action of sub-units, but at the same time also offered the necessary rigidity for the sub-units that facilitate auxetic action (Grima, N, J, 2010).

The fourth structure shown in Figure 39 was created from close-celled foam and a refined version of this was considered for final testing. Although buckling did improve slightly when compared to the previous version that was made from open-celled foam, it was observed that the structure might needed some additional mechanism to promote further vertical growth.

Figure 39: Buckling Triangles-Fourth Version

In order to enable a more dramatic growth along the Z-direction, embroidery floss was threaded through the structure to act like harnesses that would induce the buckling action. The entire sequence of manufacturing the fifth structure and its working mechanism has been discussed in detail in the subsequent chapter.

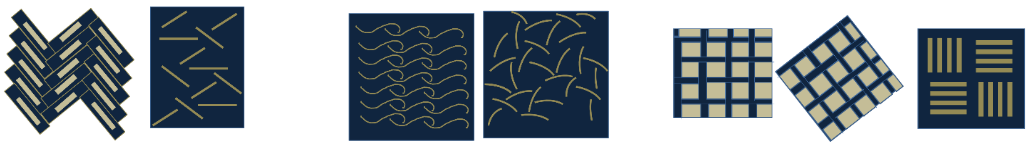
CHAPTER 3: METHODOLOGY

Towards the end of the pre-research phase, *twisting, pop-up and buckling* mechanisms were identified as three viable directions to pursue in creating Z-expandable auxetic textile structures (Pleat pop-up, Slot pop-up and Buckling Triangles).

This chapter discusses the design and manufacturing steps of the prototype which was considered for final testing. The working mechanism of each prototype has been explained with the help of detailed conceptual diagrams that demonstrate the Z-expandable auxetic action. Figure 41 captures thumbnails of all the preliminary and final prototypes that were created as part of this study.

Figure 40: Twisting, Pop-up and Buckling Mechanisms

Herringbone Structures *Wave and Arc Structures* *Swastika (卐) inspired structures*



(i)Paper prototypes with slits

(ii)Open-celled foam prototypes

(iii)Closed-celled foam prototypes

(iv) Origami prototypes

(v)Fabric and industrial felt/foam integrated prototypes

Figure 41: Thumbnails of Z-expandable auxetic prototypes

3.1 Pleat Pop-up: Working Principle and Manufacturing Process

At this point, it was clear that in order to get this concept to work, the structure had to satisfy both the conditions stated below:

(i) The pleats of the base felt fabric need to transform from a planar 2D to 3D through the radial movement.

(ii) The concentric shapes need to spiral out from a planar 2D shape to a 3D spring

Version 3 satisfied only the second condition. In exploring ways to ensure that the pleats lie absolutely flat in version 4, securing the pleats down by sewing was identified as a viable route. It was decided that a stretch fabric would replace the elasticated yarn in this prototype, since it would be easier to secure pleats to fabric than to elasticated yarn. Version 4 worked very similar to version 3. In the absence of a tensile force, the pleats would lie flat. When subjected to a tensile force, the pleats would move in a radial manner and orient itself perpendicular to the horizontal. As the pleats move in a radial manner, the concentric shapes also spiral out (expand) to offer impact protection. Figure 42 explains the basic working principle.

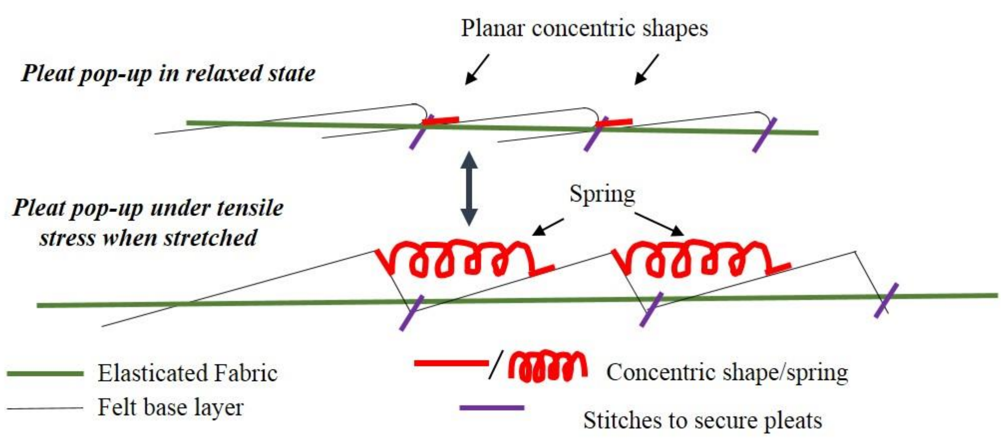


Figure 42: Basic working principle of Pleats pop-up version 4

Once the pleats were heat-set into the base felt fabric, a piece of nylon-spandex stretch fabric (cut to the same dimensions of the heat-set fabric) was sewn onto the reverse side of the felt fabric, such that every edge of the pleat was secured to the stretch fabric. Securing every pleat to the elastic is a critical step in the process. Based on pre-research, it was evident that skipping this step would not bring forth the desired effect. Concentric foam shapes were secured between the pleats for this prototype as well. This structure was considered for final testing because it satisfied both the conditions that it was designed for—i.e., it allowed for 2D to 3D transformation of the pleats, as well as the concentric shapes, when subjected to a tensile stress.

Figure 43: Pleat Pop-up Version 4 (i) Relaxed State (Top) (ii) Stretched (Bottom)

3.2 Slot Pop-up: Working Principle and Manufacturing Process

The slot pop-up structure was made from two sheets of foam with square shaped slots cut out alternately (indicated in orange) as shown in Figure 44. Corresponding flaps marked with the same number from the bottom and top layers were spot welded together. For instance, the slots marked ‘1’ from each layer was spot welded together, and so on, all the way till 8.

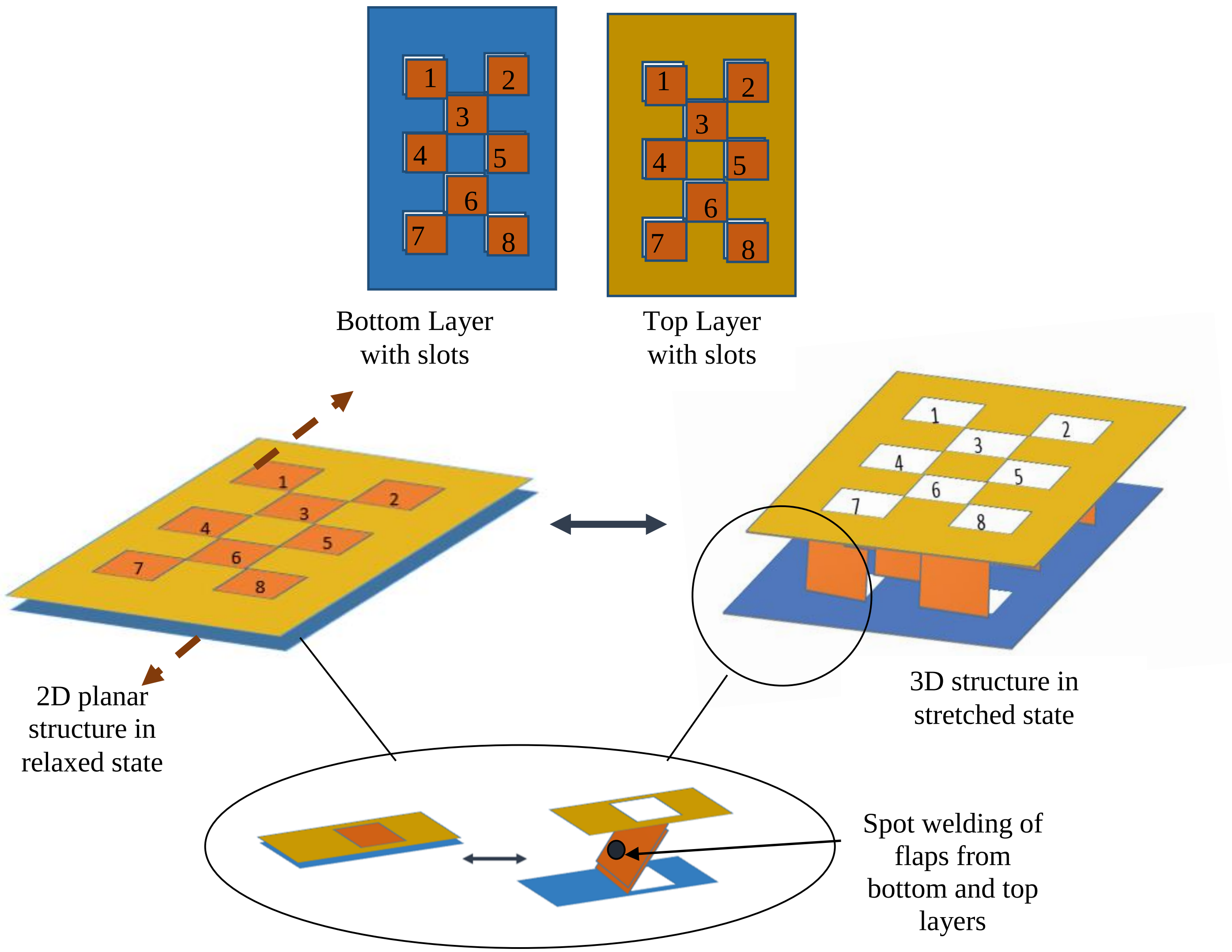


Figure 44: Slot Pop-up Action

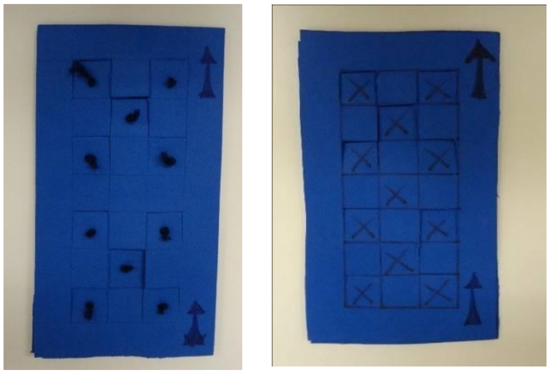


Figure 45: (i) Spot welded structure (ii) Stitched structure

For experimentation purposes, one prototype was spot-welded using superglue, while the other was fastened with a single stitch connecting two corresponding flaps (Figure 45). Among the two, it was observed that the spot welded structure demonstrated slight stiffness in and around the welded regions where each flap was secured, whereas flaps secured with stitches allowed for relatively easier movement of the entire structure and proved to be more stable.

Figure 46: Slot pop-up structure

Figure 46 shows the final prototype considered for testing. As shear force is applied, the horizontal flaps rise up in a radial manner and maximum auxetic action is observed when the flaps become vertical (i.e., perpendicular to the horizontal). Beyond this point, when further shear force is applied, the vertical flaps move radially and eventually become horizontal again.

3.3 Pleat Pop-up: Working Principle and Manufacturing Process

This first step to manufacturing this structure is to place a triangular template (as shown in Figure 47 (i)) over a sheet of foam and to cut out the necessary units using scissors, retractable cutting knife or laser cutter.

Figure 47: (i) Cutting triangular sub-units from foam using retractable knife (ii)Lay Planning

For optimum usage of foam, the following lay plan (Figure 47 (ii)) with adjacent triangular units facing opposite directions is recommended. The next step is to connect the sub-units. Two sub-units are connected with the help of a stitch.

The simplest structure (Figure 48) combines four sub-triangular units. Bigger structures can be created by adding more rows and (or) columns of sub-units. The third step is to punch holes that are close to the vertices of the triangles and an embroidery floss is to be threaded through the holes for tensioning purposes in a crisscross manner, similar to a pattern followed in shoelaces. In order to prevent the floss from cutting into the polyurethane foam, the punched holes were secured with metallic eyelets.

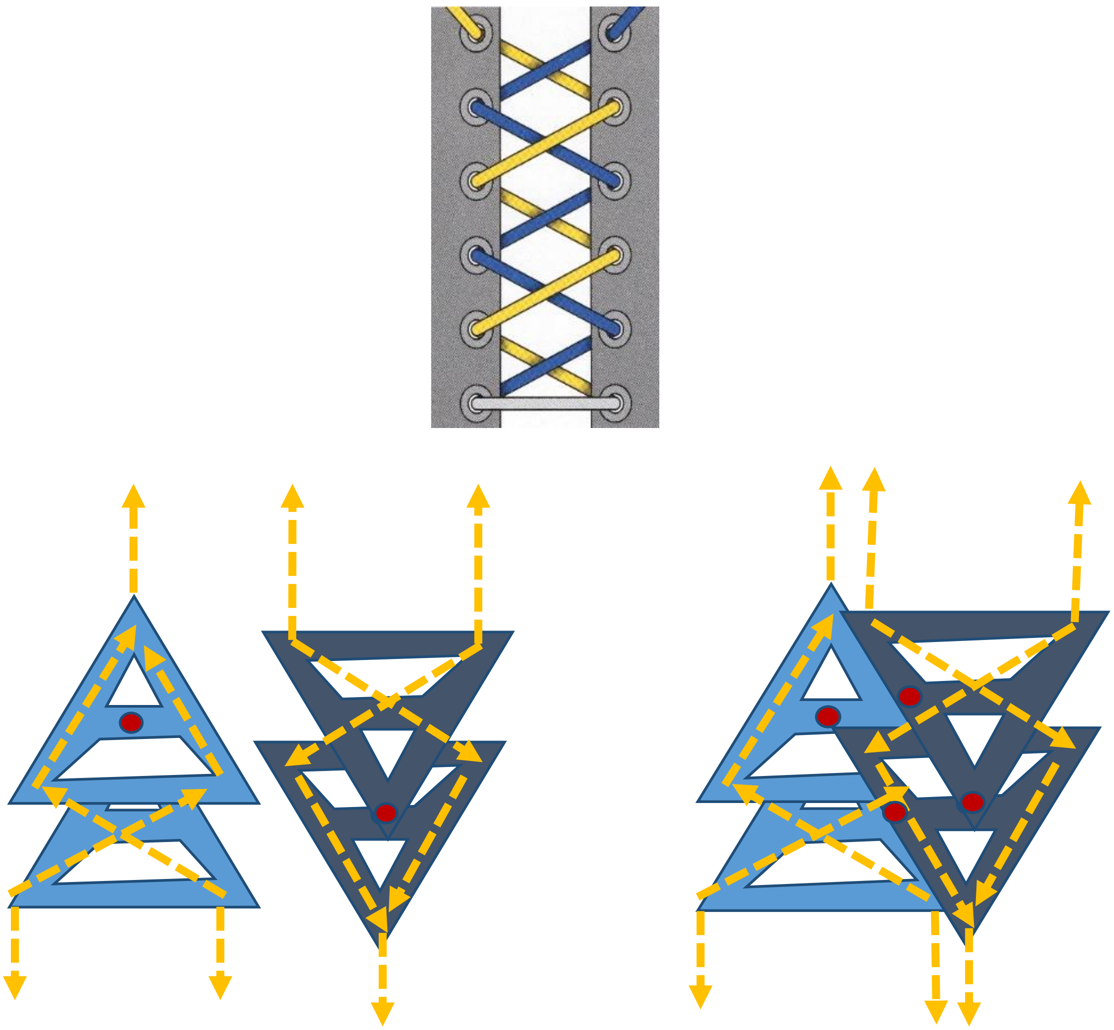


Figure 48: (i) Crisscross Shoelace pattern (top image from White, M., 2007) (ii)Buckling Triangle Columns (left) (iii) Simplest Structure for Buckling Triangles (right)

The red dots indicate the sewn hinges that are necessary for the integrity of the structure. The triangles in dark blue are indicative of an overlap (i.e., triangles in dark blue rest above the light blue colored triangles).

Tensioning the structure is achieved by simultaneously pulling the floss from both sides of the structure. On tensioning the structure, the horizontal bars in the triangles buckle. When the tension is released, the horizontal bars straighten out and relax.

The buckling along the light blue column happens along a particular direction, while the buckling along the dark blue column happens in the opposite direction. In other words, when the structure is tensioned along one plane, it buckles along the perpendicular direction, where the dark blue colored sub-units buckle upwards and the light blue colored sub-units buckle downwards. Thus, the auxetic effect is induced in this structure by the simultaneous buckling along opposite directions as shown in Figure 49.

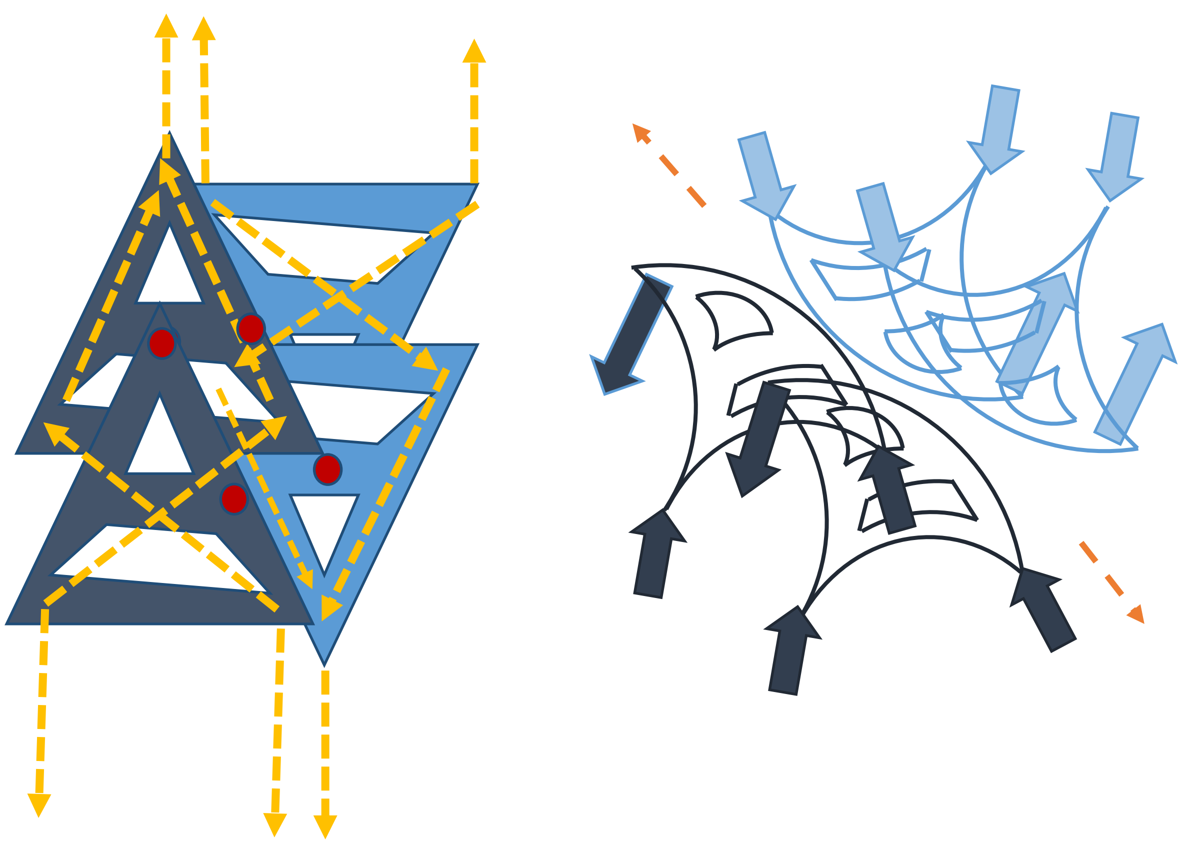


Figure 49: Buckling Action

The choice of floss is important in impacting the tensioning of the structure, since the floss acts like a harness. Threading the floss into the structure without metallic eyelets made it resistant to growth along the Z-axis. The use of metallic eyelets enabled easier movement of the floss and also promoted auxetic action in the structure.

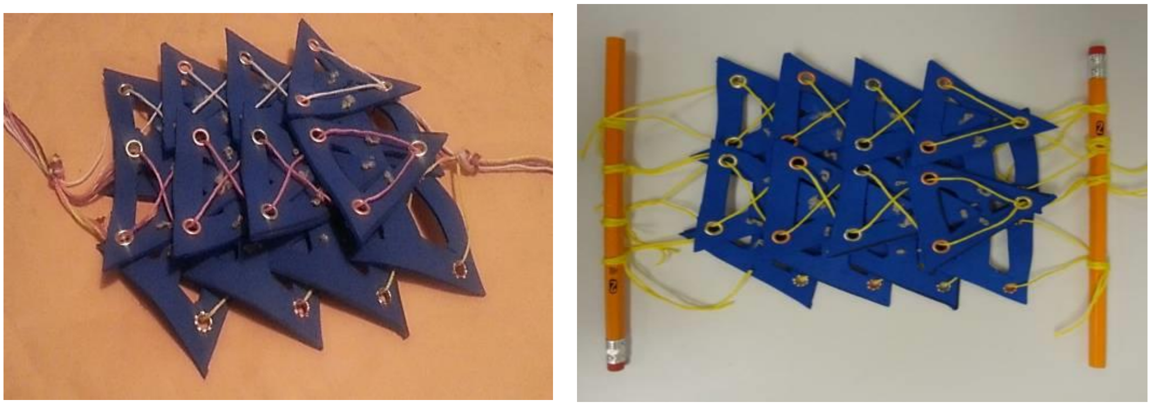


Figure 50: Z-Expandable Buckling Triangles, with and without support rods

It was observed that the top and bottom portions of the structure had a tendency to bend in an oblique manner. In order to prevent this, two wooden pencils were secured to the threads, on the top and bottom of the structure to promote overall linear movement of the entire structure while tensioning and to provide stability, as shown in Figure 50.

3.4 Testing the Samples

Z-expandable buckling triangles, slot pop-up and pleat pop-up structures were considered for final testing. Images and videos were captured. The images in the subsequent sections (Figures 52-54) show front and side views of the prototypes, when subjected to a tensile stretch test on the Instron. Each prototype was captured in its relaxed state (before extension), during partial extension and an extension at which the structure grew to its maximum thickness.

Figure 52 (i) and (ii): Z- Expandable Pleat Pop-up in relaxed position

Figure 52 (iii) and (iv): Z- Expandable Pleat Pop-up in semi-stretched position

Figure 52 (v) and (vi): Z- Expandable Pleat Pop-up—stretched to maximum thickness

Figure 53 (i) and (ii): Z-Expandable Slot Pop-up in relaxed position

Figure 53 (iii) and (iv): Z-expandable slot pop-up in a semi-stretched position

Figure 53 (v) and (vi): Z- expandable Slot Pop-up—stretched to maximum thickness

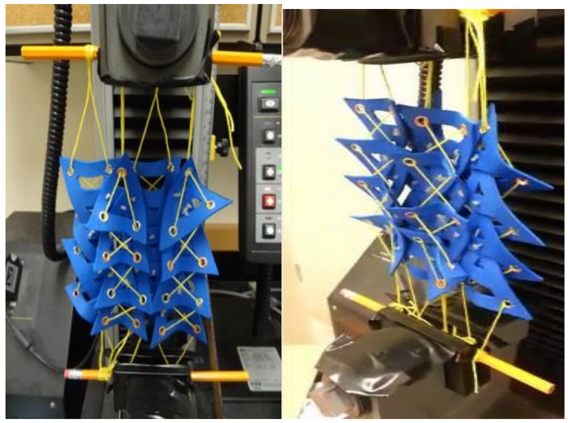


Figure 54(i) (ii): Z- Expandable Buckling Triangles in relaxed position

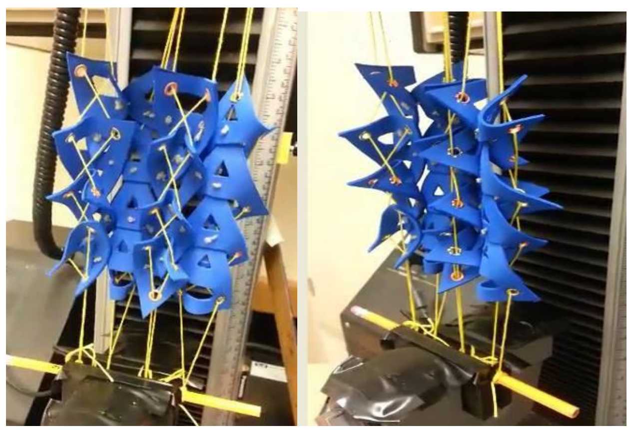


Figure 54 (iii) (iv): Z- Expandable Buckling Triangles in a semi-stretched position

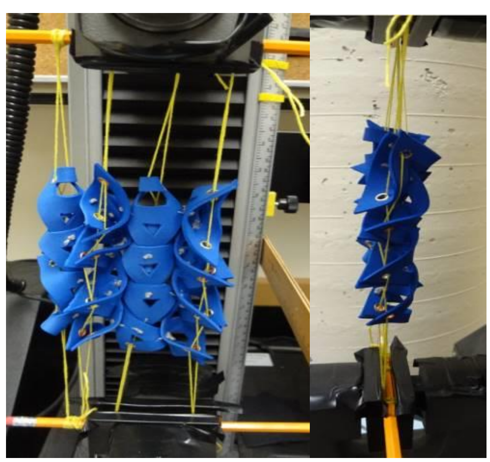


Figure 54 (v) (vi): Z- Expandable Buckling Triangles-- stretched to maximum thickness

The ASTM D5034-09 '*Standard Test Method for Breaking Strength and Elongation of Textile Fabrics* and ASTM D1777-64 '*Standard Test Method for Thickness of Textile Material*' was adapted for the purpose of this study. The structures were made from 0.125 inch thick closed-cell polyurethane sheets. The testing was performed on the Instron 5544 Constant Rate of Elongation (CRE) type machine in which the specimen is subjected to elongation of 0.50 inches at a uniform rate. The amount of stretch or elongation that the specimen undergoes during tensile testing is expressed in the form of strain. For the purposes of this study, engineering strain (the ratio of the change in length to the original length) of the specimen was determined for the Y and Z axes.

Using these values, the engineering Poisson's ratio (ratio of the transverse strain to the longitudinal strain) was determined. Specimens were mounted on the clamps manually. Clamp liners were used in order to preclude slippage and minimize specimen failure in the clamped areas. The machine had a steel rule running along the longitudinal direction to measure length. A ruler was also attached along the transverse direction in order to measure the change in thickness (Figures 55 (i),(ii) and (iii)). Particularly with the Pleat pop-up structure, there was some noticeable non-uniformity in which the spiral structures uncoiled and recoiled during Z-expansion. This non-uniformity could be partly attributed to the centrifugal and centripetal action of the spirals. In addition to this, perhaps cutting out the spirals with more precision, orienting all the spirals in a similar fashion and a change in type of material could help overcome this problem non-uniform movement. Length and thickness measurements were recorded. Images and videos of the mounted structures capturing front and side views in relaxed, semi-stretched and stretched positions were captured.

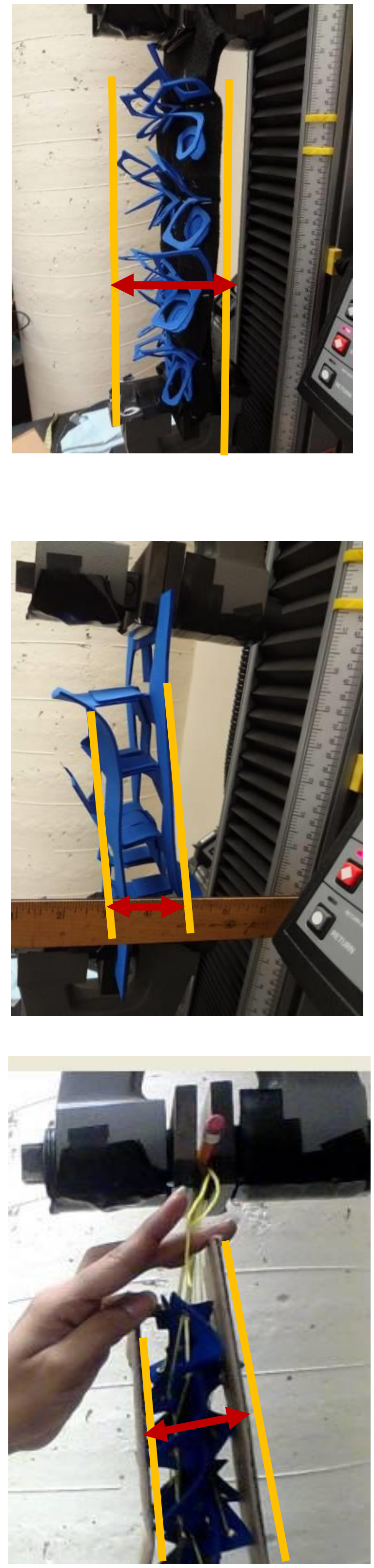


Figure 55 (i) (ii) and (iii): Measuring Thickness of Samples

CHAPTER 4: RESULTS AND DISCUSSION

4.1 Summary of Results

This section presents the data from testing the structures. For various lengths of stretch, corresponding thicknesses were recorded, until two consecutive thickness values were obtained, indicating saturation (i.e., prototypes showed overall resistance to movement). These consecutive values are encircled in red in the table. Testing beyond these points resulted in failure. Measurements were taken at relaxed (indicated in green in the table) and extended positions (the maximum thickness for auxeticity is highlighted in orange in the table). The decrease in thicknesses of the Pleat pop-up and Slot pop-up for measurements beyond this limit is because these are *positional semi-auxetics* (refer section 4.2.1).

Z-Expandable Pleat Pop-up		
Length vs. Thickness		
No.	**Length (Inches)**	**Thickness (Inches)**
1	11	1 (spiral sticks out obliquely) and 0.25 (actual)
2	11.5	2
3	12	2.25
4	12.5	2.5
5	13	2.75
6	13.5	3
7	14	2.75
8	14.5	2.5
9	15	2.25
10	16	2.25

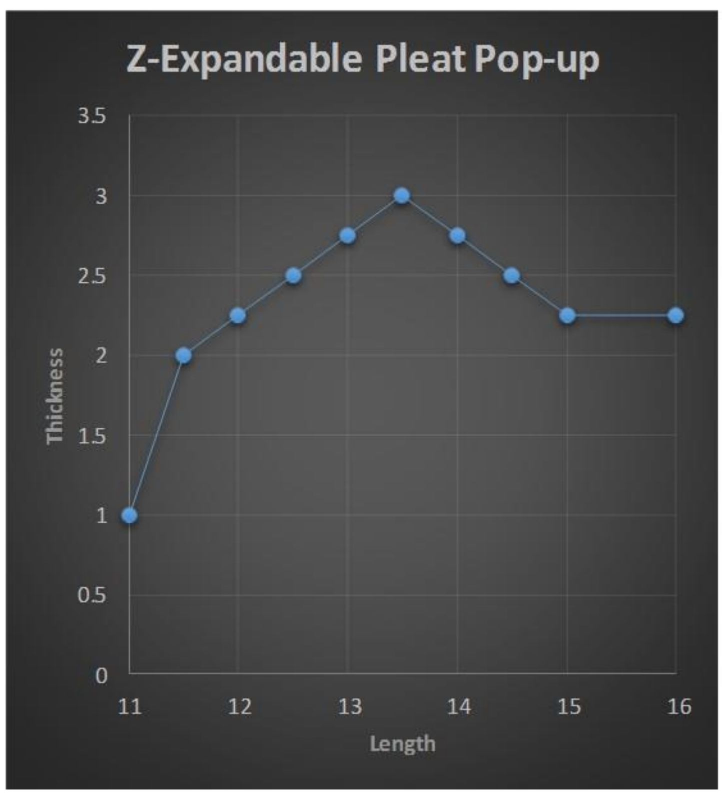


Figure 56: Z-Expandable Pleat Pop-up Length versus Thickness

Z-Expandable Slot Pop-up		
Length vs. Thickness		
No.	Length (Inches)	Thickness (Inches)
1	9.25	0.25 (when mounted in relaxed position) and 0.125 (actual)
2	9.5	0.5
3	9.75	0.75
4	10	1
5	10.5	1.25
6	11	0.75
7	11.5	0.5
8	12	0.25
9	12.5	0.25

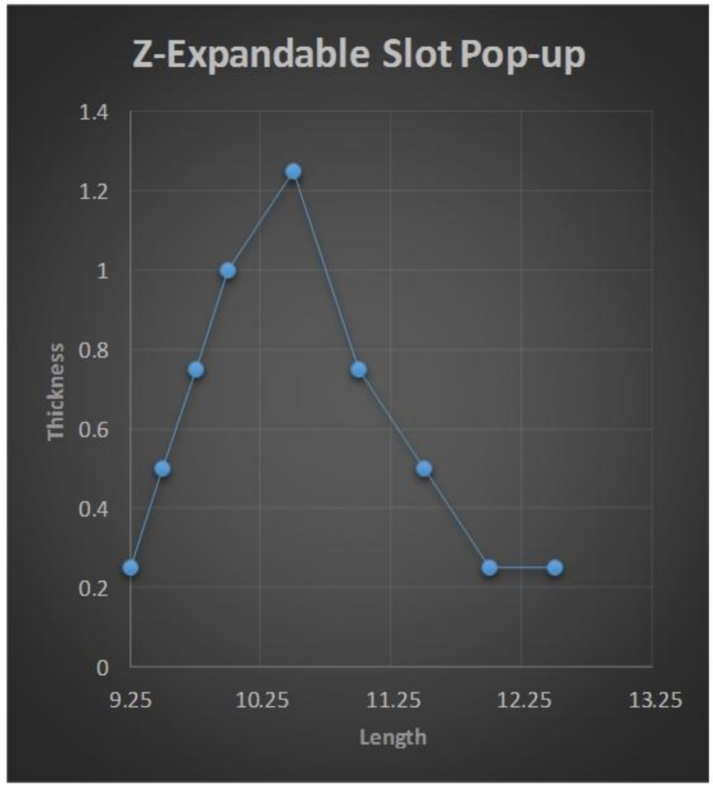


Figure 57: Z-Expandable Slot Pop-up Length versus Thickness

Z-Expandable Buckling Triangles		
Length vs. Thickness		
No.	Length (Inches)	Thickness (Inches)
1	9.25	0.25 (when mounted in relaxed position) and 0.125 (actual)
2	9.5	0.75
3	9.75	1
4	10	1.5
5	10.5	1.75
6	11	2
7	11.5	2

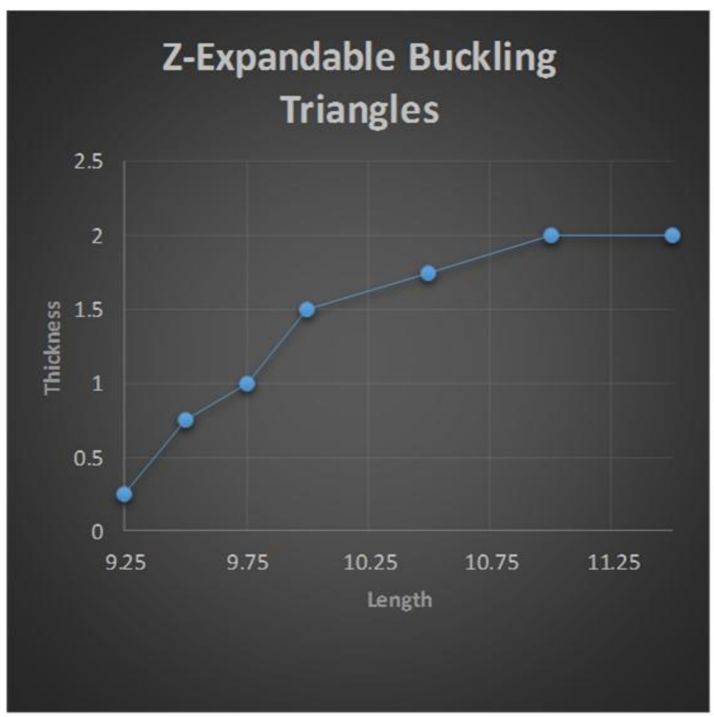


Figure 58: Z-Expandable Buckling Triangles Length versus Thickness

Auxeticity of both the structures were determined from the Engineering Poisson's ratio values, based on the formula provided below.

$$\text{Engineering Poisson's Ratio} = -\left(\frac{\text{Strain}_{\text{Transverse}}}{\text{Strain}_{\text{Longitudinal}}}\right) = -\frac{\left(\frac{T_2-T_1}{T_1}\right)}{\left(\frac{L_2-L_1}{L_1}\right)}$$

It is to be noted that in the case of a conventional non-auxetic material, when the value of Strain $_{\text{Longitudinal}}$ is positive, Strain $_{\text{Transverse}}$ is negative because a stretch along the longitudinal direction will result in a compression along the transverse direction. The formula is usually assigned a negative sign, so that the resultant Poisson's ratio is positive for conventional materials. However, in the case of auxetic materials, since a stretch along the longitudinal direction would result in expansion along the transverse direction, the Strain $_{\text{Longitudinal}}$ and Strain $_{\text{Transverse}}$ will carry positive signs, and therefore, the resultant Poisson's ratio will be negative. The samples were subjected to ten cycles of stretch and the average measurements at relaxed and extended positions were used to calculate the Poisson's ratio corresponding to each structure.

	Pleat Pop-up		***Slot Pop-up***		***Buckling Triangles***	
	Length (inches)	***Thickness (inches)***	***Length (inches)***	***Thickness (inches)***	***Length (inches)***	***Thickness (inches)***
Measurements at relaxed position (before extension)	11 (L_1)	0.25 (T_1)	9.25 (L_1)	0.125 (T_1)	9.25 (L_1)	0.125 (T_1)
Measurements at extended position (at maximum thickness)	13.5 (L_2)	3 (T_2)	10.5 (L_2)	1.25 (T_2)	11 (L_2)	2 (T_2)
Engineering Poisson's Ratio	**-49**		**-67**		**-79**	

Table 4: Measurements at relaxed and extended positions

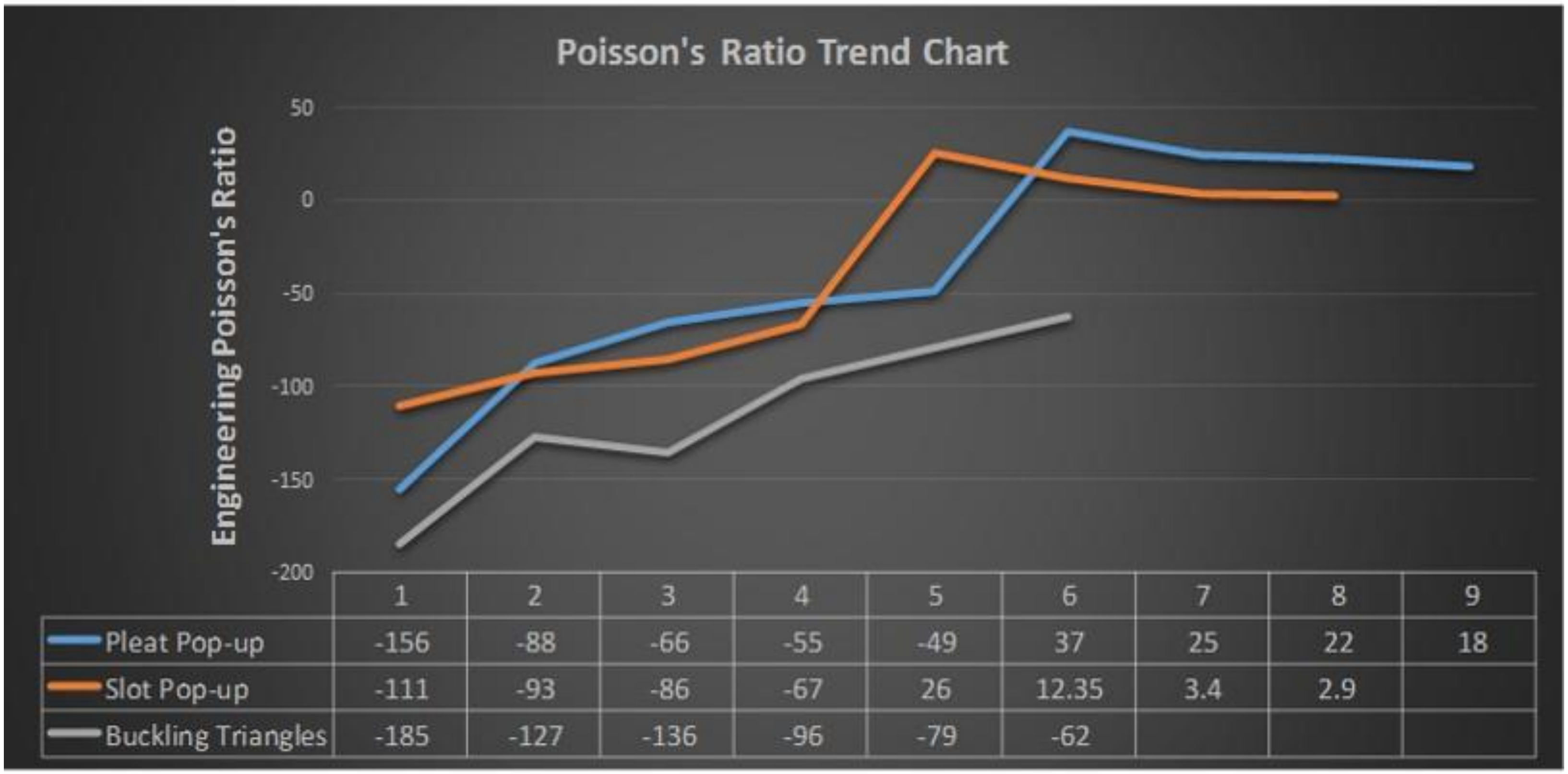


Figure 59: Poisson's ratio trend chart

Figure 59 represents the Poisson's ratio variation across all three structures for 9 intervals. The Poisson's ratio changed from negative to positive for both the Pleat Pop-up as well as the Slot Pop-up, at the 6th and 5th intervals respectively. The Buckling triangles structure however retained its auxeticity throughout, as evidenced by negative a Poisson's ratio at every interval.

4.2 Foundation and Geometry of Z-Expandable Auxetics

4.2.1 *Characterization*

The structures considered for this study are *anisotropic* because they do not have identical properties along every direction. Poisson's ratio for *isotropic* materials that stretch uniformly in all directions ranges between -1 to 0.5. Anisotropic materials can carry an arbitrary value of any magnitude (Ting, T. C. T., & Chen, T., 2005), as is the case for these three structures. In the recent past, there is an emerging school of thought that such anisotropic materials that exhibit conventional behavior in one direction and auxetic behavior in another plane should be classified as *directional semi-auxetics* (Lim T.C., 2015). All three prototypes created in this study come under this category. From observing a Poisson-shear material such as the Slot pop-up for example, it is apparent that by virtue of the structure, it is characterized by a negative Poisson's ratio along the Z direction and by positive Poisson's ratios along other directions.

Anisotropic materials that possess two Poisson's ratios at different points when subjected to stretch in a given direction, are termed as *positional semi-auxetics* (Lim T.C., 2015). The Slot pop-up and Pleat pop-up structures come under this category, since the Poisson's ratios of these change in signs (from negative to positive and vice-versa) beyond a particular length of stretch.

4.2.2 *Structural Analysis*

Analyzing the factors influencing the structures of two-dimensional auxetics is generally less complex (Grima, J, et al., 2012) than that of 2D to 3D transformable anisotropic structures. For some of these structures (such as the Buckling Triangles and Slot Pop-up), the parameters are somewhat more well-defined than others. This section discusses the factors that influence structures of the three Z-Expandable auxetics created as part of this study.

<u>Buckling Triangles</u>

- *Rigidity of the sub-units*- In the case of the Buckling Triangles structure, replacing open celled-foam with close-celled foam helped in creating a dramatic Z-expansion. Since open-celled foam lacked rigidity, it allowed for internal stretching of individual units. Even though the individual sub-units of open-celled foam buckled slightly, the extent of buckling of the structure along the Z-direction was limited because of the simultaneous internal stretching of the sub-units along the Y-direction. Close-celled foam on the other hand was comparatively more rigid than open-celled foam and therefore, the structure could achieve maximum buckling.
- *Size of the Sub-unit*- The size of the triangle is an important criterion for this structure. A smaller triangle would allow for lesser buckling and therefore lesser Z-growth, while a larger triangular sub-unit would promote relatively more buckling and therefore more Z-directional growth, as shown in Figure 60.

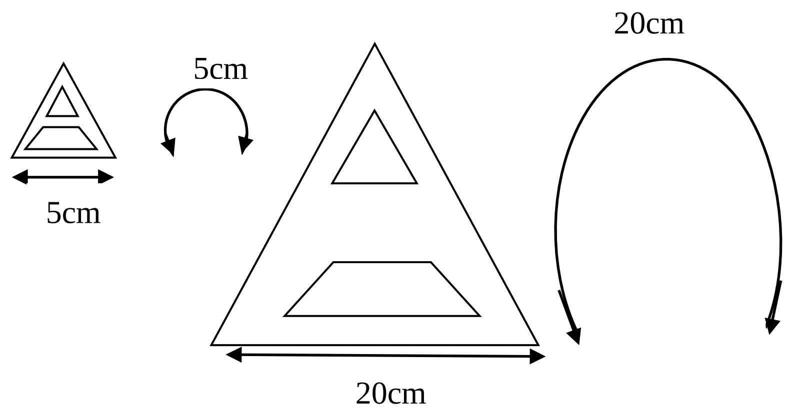


Figure 60: Extent of buckling

- *Shape of Sub-unit*- The triangular cross-section and horizontal beam facilitate the buckling action. There is a trade-off between the triangle's base and height that would influence the extent of buckling and interlocking. Increasing the length of the horizontal beams would result in triangles with a larger base, thereby enabling greater buckling, due to an increased altitude. However, increasing the base length without altering the altitude would result in structures that have a less pointed peak. A well-defined triangular peak is necessary for the interlocking of triangular sub-units from each column of the structure (Figure 61).

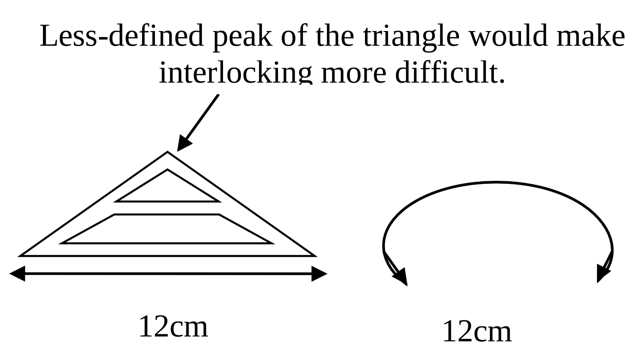


Figure 61: Less-defined triangular peak

- *Hinges*- Poisson's ratio is influenced by the angles created from buckling and interlocking in the case of the Buckling Triangles structure. Further, hinges are located in such a manner that it does not preclude the movement of units.
- *Aperture shape*- The aperture shape is triangular and trapezoidal, allowing the sub-units to interlock, in addition to allowing for shape change and flexibility.

  When sub-units are assembled, the triangular peak and aperture in the structure slots into the trapezoidal aperture to create an interlocking effect. The change in aperture is shown in Figure 62.

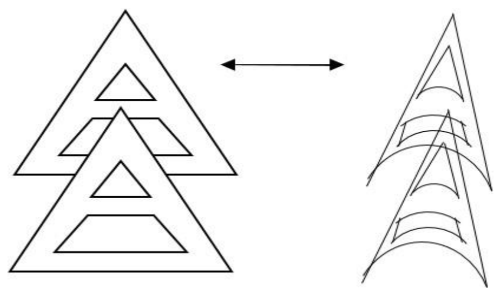


Figure 62: Change in aperture during 2D to 3D transformation

- *Embroidery Floss and Eyelets*- Manipulating the harnesses allows for growth and recovery of the structure. The free movement of the embroidery floss (harnesses) is important for tensioning the structure and enable dramatic growth in the Z-direction. Since alternate columns of sub-units are oriented in one particular direction, harnesses pulling from columns 1 and 3 would control the sub-units in those columns in a particular direction and harnesses pulling from rows 2 and 4 would control the sub-units in those columns in the opposite direction. This simultaneous control of sub-units from both ends results in upward and downward buckling.

The use of eyelets is essential to prevent the floss from cutting into the foam and to enable free movement. Floss with low twist would work better than floss with high twist.

<u>Slot Pop-up</u>

- *Hinge Angles*- Hinging angles created from the radial action of the flaps in this structure influence the Poisson's ratio of this structure.
- *Dimension of aperture and flaps*- Varying the dimensions of the aperture and flaps can provide different effects. For example, a longer flap would result in greater Z-growth.
- *Fastening*- The fastening used to secure each pair of flaps is an important contributing factor. As discussed in the methodology section, using glue restricted the mobility as against fastening the flaps using a single stitch.
- *Flap Rigidity and Thickness*- Varying the rigidity and thickness of the flap could have a consequence on the Poisson's ratio. From an impact protection standpoint, having a flap that is made from a material that absorbs forces would help in deflecting normal forces. However, too rigid a material may preclude free movement. Therefore, selecting a flap material with optimum rigidity and thickness is critical to this structure, since it would directly influence the growth and recovery of the structure.

Pleat Pop-up

In the Pleat pop-up, it is important to bear in mind that during the 2D to 3D transformation, unlike the compression and release action of a regular spring, the spiral structures demonstrate a centrifugal action while spiraling out and a centripetal action while spiraling back into their 2D forms. However, some basic structural parameters of a compression spring are also common to this structure (Figure 63).

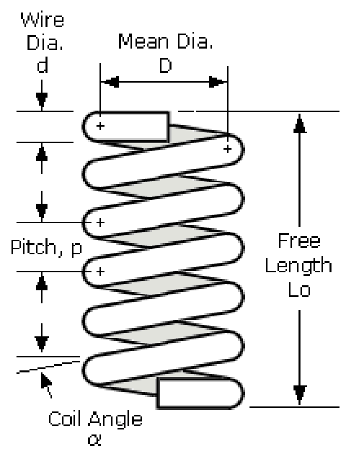


Figure 63: Properties of a compression spring

- *Rigidity/Thickness of Spirals and Pleats*- Optimum rigidity and thickness of these materials is critical for actuating the Z-expansion. It is important that these have good compressive strengths, but at the same time facilitate free movement. The *Spring Index* is the ratio of the mean coil diameter to wire diameter. A low index would indicate a higher degree of tightness (i.e., a thick coil wound to a small diameter would increase the tightness). An increased thickness would improve the force of a compression spring and also its stability. A rigid spiral would show more resistance to movement in the Z-direction.
- *Nature of Spirals*- Increasing the number of spirals would result in a bigger spiral structure. Figure 64 captures spring variations that could potentially be

incorporated in the structure. Gluing the central points of two circular spiral structures would result in an hourglass spring and outermost coils of two circular spirals would result in a barrel spring. Shape and orientation of the spirals can influence the number of spirals packed in a row. Several square-shaped spirals can be accommodated in a pleat without any gap.

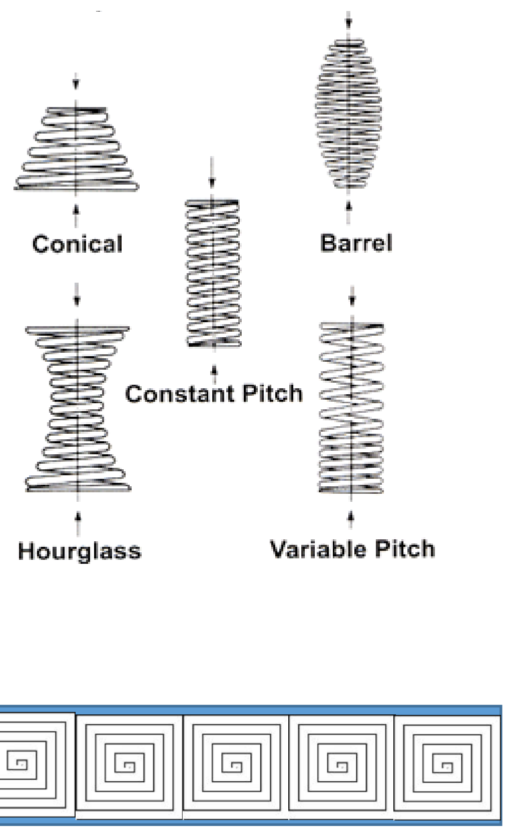
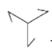


Figure 64: (i) Spring Variations (Top) (ii) Square shaped springs (Bottom)

- *Fastening*- Securing elastic to the pleats is a contributing factor for the actuation of this structure. When stretched along the Y-direction, the secured elastic allows for every individual pleat to move radially, stand up and open out, after which the spring structures spirals out.

4.2.3 *Auxetons*

As discussed in the background section, auxetons are the basic 2D structural units with three contact points that make up an auxetic structure (Blumenfeld and Edwards, 2012). Putting these auxetons in perspective of this research, it can be posited that these transform from 2D to 3D during the growth phase of the Z-transformation. In the Pleat Pop-up structure, the auxetons  and  bring forth an auxetic transformation that is similar to the radial pleat action and the uncoiling of spirals. In the Slot Pop-up structure, the auxeton  represents an action similar to the radial action that occurs during growth and recovery. In the Buckling Triangles structure, the auxetons  and  come into action during the resizing and buckling of triangles during growth and recovery.

In this section of the chapter, the auxetons for the three Z-expandable auxetic structures have been illustrated in detail (Figures 65-67). The movement of specific components have been shown separately where necessary.

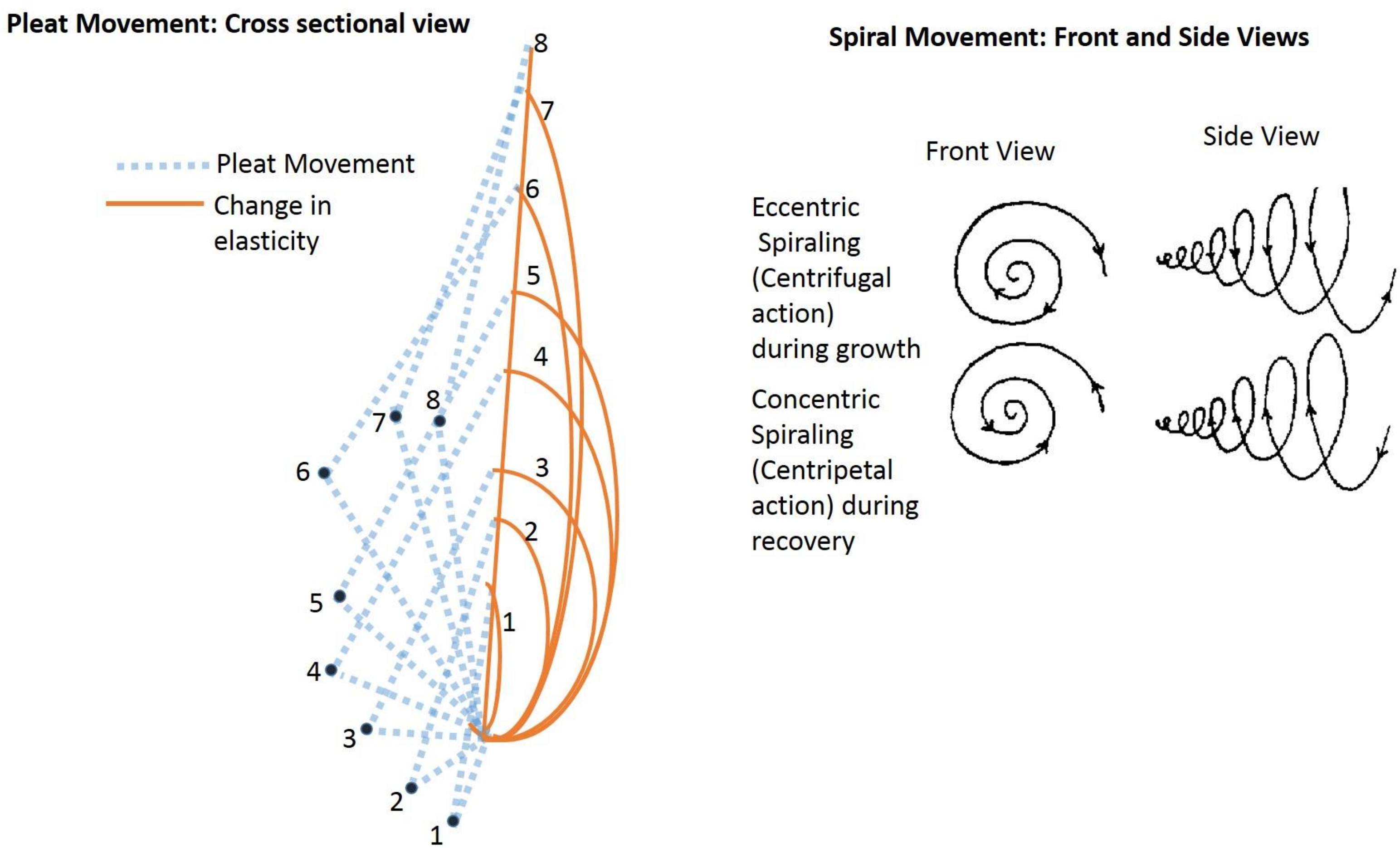


Figure 65: Pleat and spiral movement in Pleat pop-up

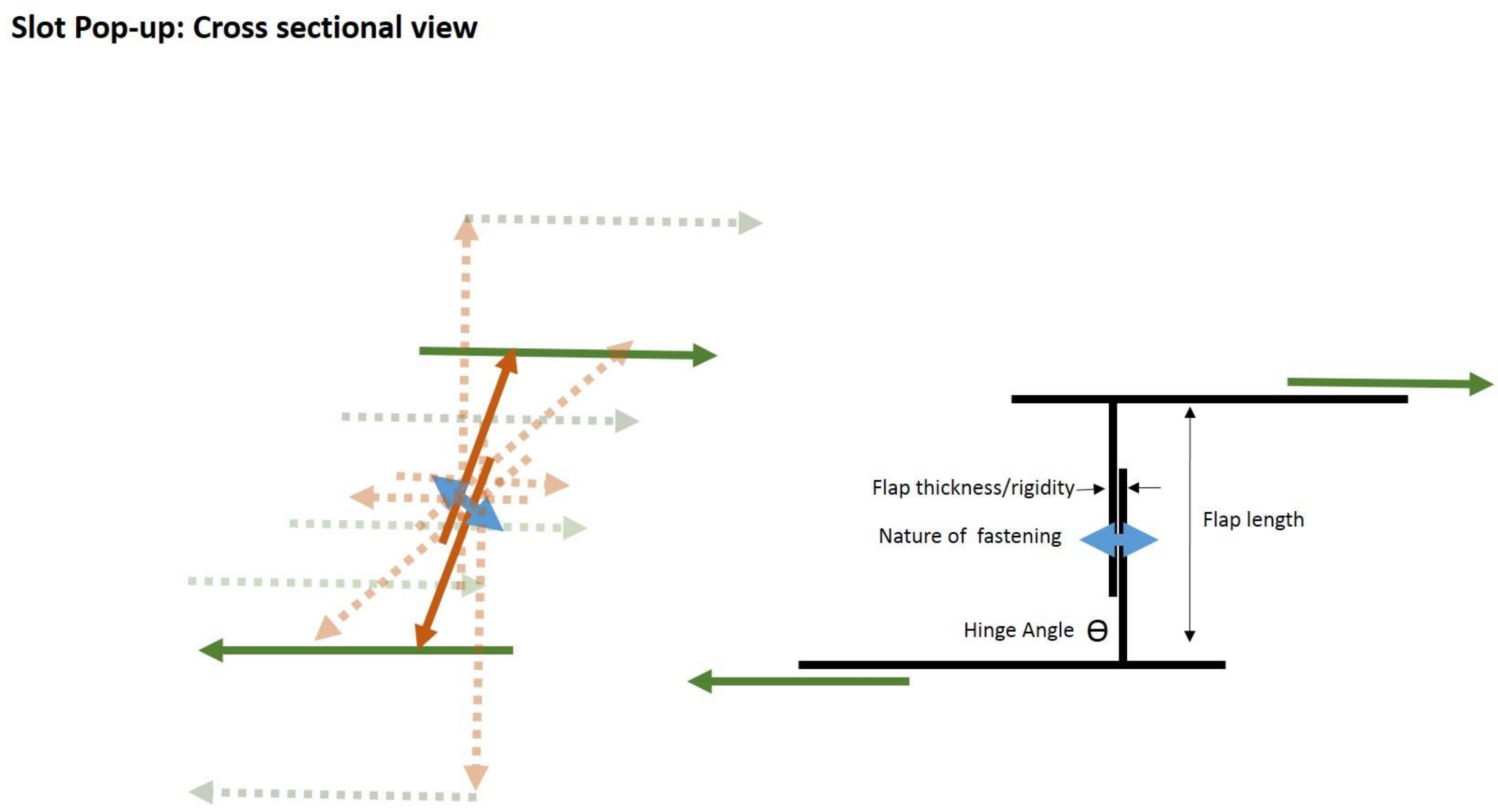


Figure 66: Auxeton for Slot Pop-up

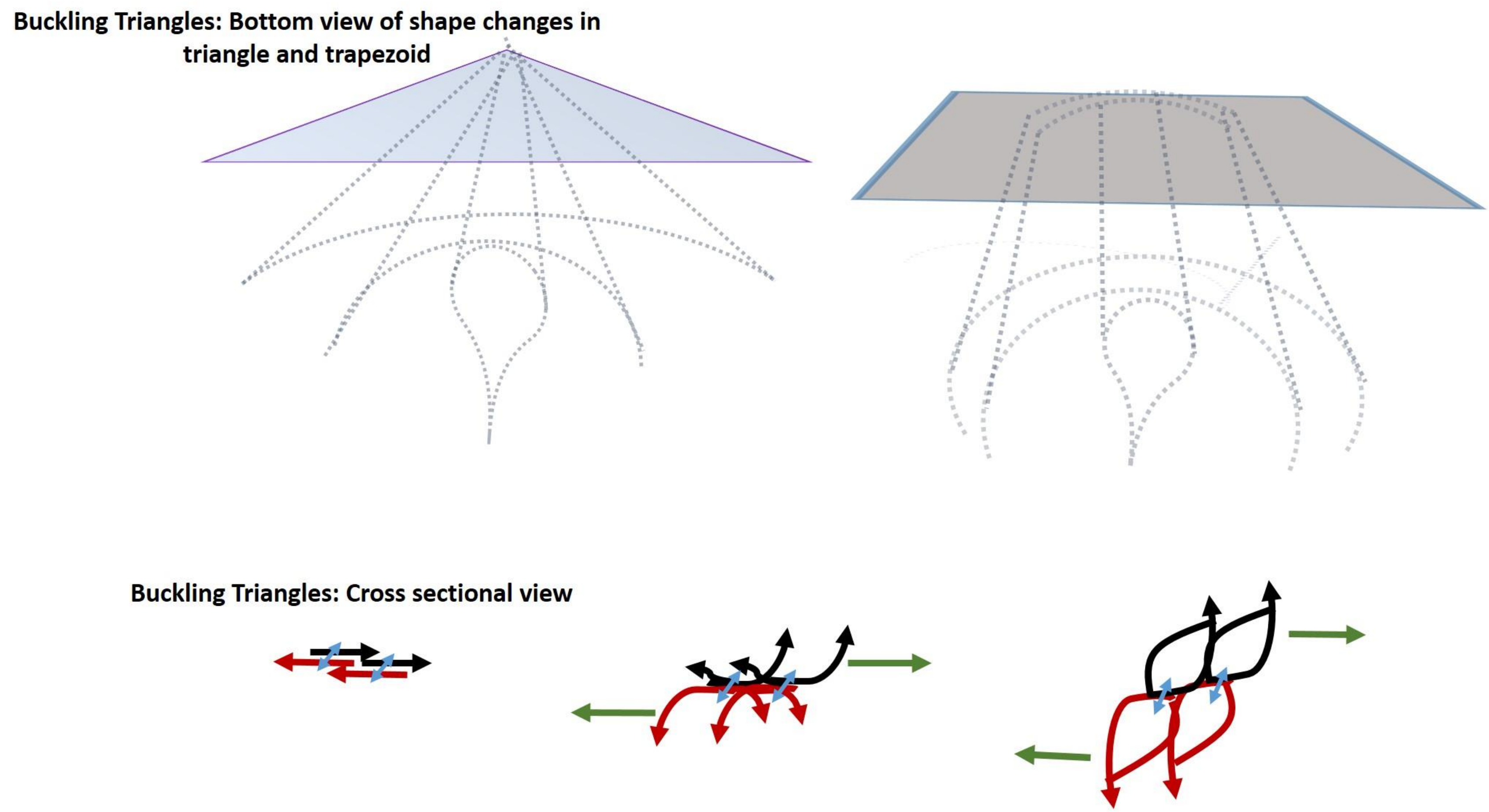


Figure 67: Auxetons for Buckling Triangles

4.2.4 Quantifying the Extent of Z-Expansion

Based on auxetons generated for the three structures, an attempt was made to identify some of the variables and to establish a mathematical relationship between the variables.

Pleat pop-up

Determining the Z-expansion in the Pleat pop-up structure is complex and is beyond the scope of this project. It can vary based on the shape of the spiral that is used. However, the following are some variables associated with the Z-expansion:

- Centrifugal Force Constant– denoted by k
- Material thickness/diameter (if circular)- denoted by d
- Length (L) or diameter (if circular)- denoted by D_{outer}
    - Mean Diameter (D) (for example, for a circular spiral, it would be (D_{outer} – d) and for a rectangular spiral, it would be (L-d)
- Number of coils- denoted by n
- Length at maximum force- denoted by L_{Max}
- Length at minimum force- denoted by L_{Min}
- Coil angle- denoted by Ɵ
- Pitch (distance between two consecutive coils)- denoted by p

Slot Pop-up

The Z-expansion in the Slot pop-up is influenced by the slot/flap depth, the type of seam as well as the hinge angle. Assuming that A is a component of the top flap and B is a component of the bottom flap, there are two possibilities. The top and bottom flap lengths could be overlapped, in which case the total slot/flap length is additive (A+B), or it could be of equal length (A=B). This would be influenced by the seam type (Figure 68).

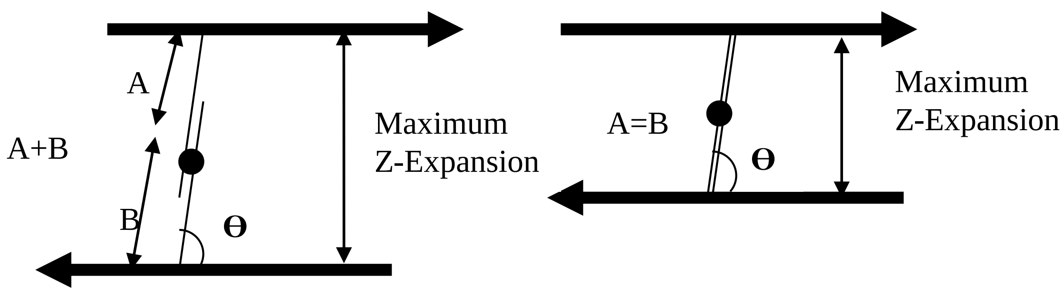


Figure 68: Slot/Flap Depth and Nature of Seam

The slot/flap depth forms the hypotenuse of a right (Figure 69) triangle and therefore, this formula can be applied to find the maximum Z-expansion:

Maximum Z-Expansion = Sin (Hinge Angle θ) X (Slot/Flap depth depending on seam)

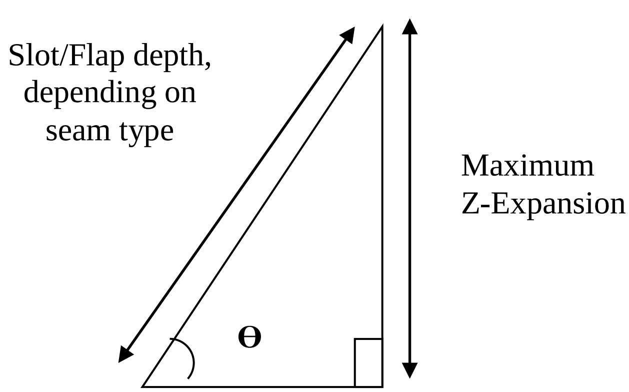


Figure 69: Maximum Z-Expansion in Slot Pop-up

Buckling Triangles

The base of the triangle is the main factor that would influence the extent of Z-expansion, as shown in Figure 70. The total height would be a sum of the heights of upward and downward buckling.

Maximum Z-Expansion = A +B, A=Height of upward buckling B=Height of downward buckling

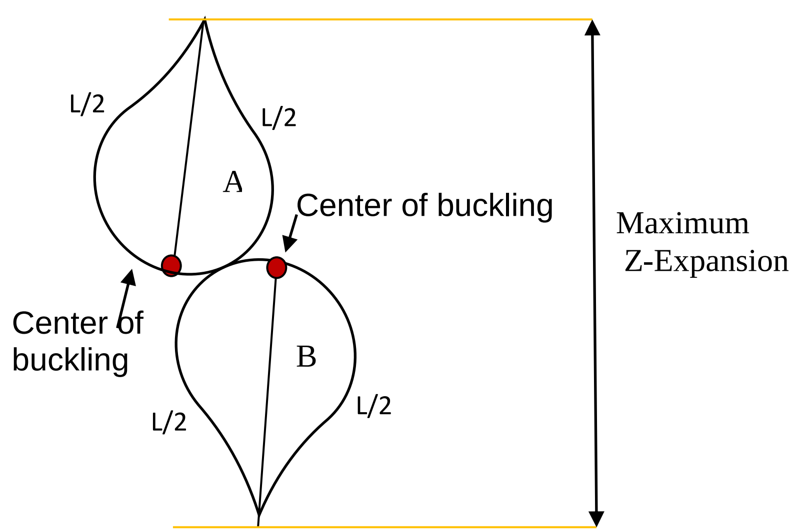


Figure 70: Maximum Z-Expansion in Buckling Triangles

4.3 Comparative Summary

A comparison of properties, applications and manufacturing methods across structures has been presented in Table 6. While all three structures are lightweight, flexible and can be easily incorporated in clothing applications, a key difference observed across prototypes is that the Buckling triangles structure retains its auxetic properties throughout, while the Slot and Pleat pop-up structures are auxetic until a particular point and exhibit what is known as a ‘reverse auxetic effect’ beyond a particular length. This may not be a point of concern if the maximum extension required for a particular application is well below this threshold.

An advantage offered by the Buckling triangles and Slot pop-up structures is that apart from offering impact protection, when stretched along the Y axis, these open out and offer enhanced air permeability. This feature can be viewed favorably, as it may help reduce sweat buildup, particularly when incorporated in applications such as kneepads which are worn close to the body.

From a mass production standpoint, the Slot pop-up structure is perhaps the easiest to manufacture, since it involves only two steps—i.e., cutting out slots and spot welding them appropriately.

	Buckling Triangles	**Slot Pop-up**	**Pleat Pop-up**
Mechanism for geometrical changes under tension	When tensile stress is applied along the Y axis, alternate columns buckle in upward and downward directions (along Z axis). The interlocking of triangular slots, coupled with buckling can help absorb force. The embroidery floss that is threaded into this structure is meant to act like a harness that activates the Z-expansion during the time of fall. The ends of the harnesses on either side of the structure could be attached to bands of fabric in impact protective clothing.	When shear stress is applied along the Y-axis, slots pop up in the Z-direction in a radial manner. The rigid slots that stand perpendicular to the direction of stretch can help absorb force (slots could be reinforced with thick industrial felt for enhanced performance). This structure could be activated in the Z-direction with the help of harnesses that exert a shear force (one set of harnesses pulling the top layer in one direction and another set pulling the bottom layer in the opposite direction) during impact.	When tensile stress is applied along the Y axis, 2D planar concentric shapes spiral out into springs, as pleats move in a radial manner. The uncoiled spirals, can help absorb force (foam was used to prove the concept, but for better performance, it is recommended that the concentric spiral shapes are cut out of thick industrial felt). This structure could be activated in the Z-direction with the help of harnesses in a garment.
Performance	Retains auxetic properties until maximum extension, with no reverse auxetic action.	Retains auxetic properties until a particular length and shows reverse auxetic effect beyond this.	Retains auxetic properties until a particular length and shows reverse auxetic effect beyond this.
Applications and features	Aside from impact protection, can provide ventilation to minimize sweat buildup. Light in weight, flexible and can be easily incorporated in a clothing system.	Aside from impact protection, can provide ventilation to minimize sweat buildup. Light in weight, flexible and can be easily incorporated in a clothing system.	Offers impact protection. Light in weight, flexible and can be easily incorporated in a clothing system.
Recommended manufacturing methods for mass production and associated challenges	-The triangular sub-units can be laser cut and the sub-units can be glued or sewn to form a bigger structure. -Eyelets can be secured using a commercial punching/attaching machine, and embroidery floss can be manually threaded through the eyelets. **Challenge:** Assembling sub-units and manual threading of floss could be time consuming.	-The foam material can be laser-cut. -Slots can be secured by industrial welding. **Challenge:** Orienting slots appropriately, prior to industrial welding could be time consuming.	-The fabric can be manipulated into pleats through the commercial pleating process. -Pleats can be secured to stretch fabric either by industrial fabric welding or sewing. -Strips of spirals can be laser cut from industrial felt and glued to the pleats. **Challenge:** Gluing strips to pleats could be time consuming.

Table 5: Comparative analysis of Buckling Triangles, Slot Pop-up and Pleat Pop-up Structures

4.4 Potential Applications

The knee is the largest hinge joint in the human body. Knee pads are a class of personal protective equipment that are designed to help absorb and spread the forces that come into play when the knee is subjected to impact (Butler, L.F., 2002). These are often used by athletes involved in contact sports. Among knee injuries, one of the most common types is that of an athlete falling on a flexed knee with the foot in plantar flexion (Clancy, WG Jr, 1983). During such times, wearing a Z-expandable kneepad would help minimize injuries.

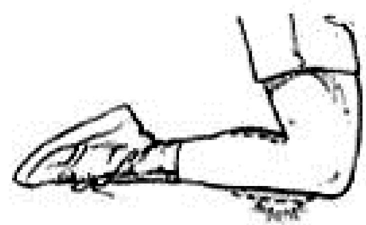


Figure 71: Sports injury where an athlete falls on a flexed knee

Another major application is that these can be incorporated in seat belts in automobiles. The degree of protection offered by a Z-expandable seat belt is likely to be much more superior to that of a 2D auxetic seatbelt, since the former will provide enhanced cushioning and shock absorption along the Z direction, when breaking hard or during the time of collision. This could prevent injury to occupants from striking steering wheels or windows and possibly even contain the situation prior to the activation of airbags in the automobile.

CHAPTER 5: CONCLUSIONS AND FUTURE WORK

5.1 Conclusions

Conventional auxetics grow along the Y axis when stretched along X axis and vice-versa. The manufacture of auxetics is generally complex. This endeavor demonstrates successful creation of easily manufacturable Z-expandable auxetic structures that can be incorporated in an impact protective application such as kneepad. These materials would grow thicker and retain their expanded configuration along the Z axis (transverse direction), for as long as there is a stress applied along the Y axis (longitudinal direction).

Various material and design directions were explored during the course of open and structured idea generation phases. *Buckling Triangles*, *Slot Pop-up* and *Pleat Pop-up* structures were fabricated from Polyurethane foam sheets. The ASTM D5034-09 for elongation *and* ASTM D1777-64 method for thickness were adapted and applied. The mechanics during growth and recovery were also identified.

The results reveal that the structures are anisotropic (do not have identical properties along every direction) and are therefore characterized by unusual Engineering Poisson's ratio values. The Poisson's ratio changed from negative to positive for both the Pleat Pop-up as well as the Slot Pop-up. The Buckling triangles structure however retained its auxeticity throughout, as evidenced by negative a Poisson's ratio at every interval.

According to a recent system of classification (Lim, T.C., 2015), all three structures come under the category of *directional semi-auxetics*, while the Slot and Pleat pop-up structures may be termed as *positional semi-auxetics*. These lightweight and flexible structures can potentially be used in impact protective applications such as kneepads, as well as in seatbelts. The *Buckling Triangles* and Slot *Pop-up* structures also offer enhanced air permeability, which could prevent sweat build-up. The variables associated with maximum Z-expansion have been identified and analyzed mathematically.

5.2 Future Work

In this study, the Engineering Poisson's ratio values obtained, were based on tensile testing of the Pleat pop-up, Slot pop-up and Buckling Triangles structures. However, in order to understand how effectively the Z-expansion of these structures can resist compressive stresses, it would be necessary to study the compressive stress-strain behavior, and compute the corresponding Poisson's ratio values for vertical and horizontal orientations. Since Z-expansion is triggered by tensile stresses in these materials, tensile impact followed by compressive impact is necessary to evaluate the compressive properties of these materials.

Axial and transverse compression measurements could be recorded while the structures are placed between parallel compression plates at a constant speed for different thicknesses (from relaxed to extended positions), using the Instron and video extensometers to capture measurements, similar to the setup used in the study conducted by Bhullar et al (2013).

Based on the three Z-expandable auxetic structures that were created as part of this study, with the help of reinforcements, the Buckling Triangles and Slot pop-up structures are expected to perform slightly better because they have a fairly ‘shielded structure’ that would offer an additional layer of protection against normal forces. The interlocking mechanism in the Buckling triangles structure as well as the two layers hinged to the slots in the slot pop-up serve as a protective shielding for these structures. The pleat pop-up on the other hand, has a fairly ‘exposed structure’ which may be more vulnerable to forces normal to the plane.

Modifications done to the slots in the Slot pop-up (in addition to reinforcing the sheets), horizontal beams in the Buckling Triangles structure (in addition to using reinforced harness threads) and the spirals in the Pleat pop-up structures (in addition to reinforcing the base fabric pleats) could prove to be useful (Figure 72).

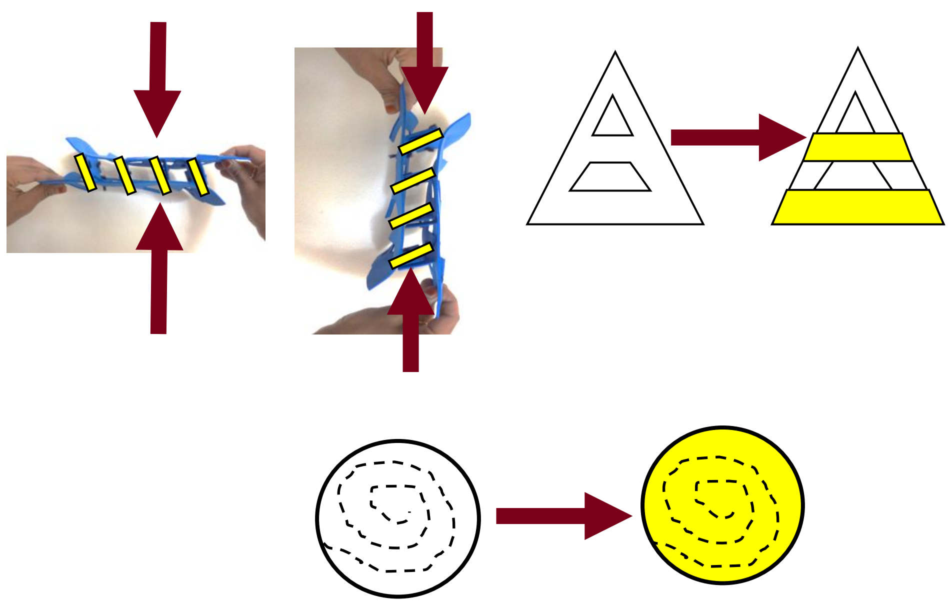


Figure 72: Modifications for reinforcing slots, horizontal beams spiral structures

Properties of the material that would allow these reinforcements to absorb force in the actuated position while remaining comfortable in the non-actuated position are important. For the purposes of compressive testing, the prototypes would require thicker, durable and flexible reinforcements, which do not preclude movement, such as energy absorbing spacer fabrics and open-celled foam, gel padding used in combination with close-celled foam.

Another approach could be to use a shear-thickening fluid, which would promote easy movement during 2D to 3D transformation, thicken or harden during impact and become fluid again when the energy from the impact dissipates through the structure.

The design of protective clothing often reflects the trade-off between protection and the mobility it offers to wearers (Askew et al., 2012). The suitability of impact protective clothing is also determined by its ability to provide realistic ease-of-motion or mobility. To this end, the movement of a chosen joint (such as the knee) can be tracked in relation to the dimensional changes of the chosen auxetic structures with the help of motion capture studies. Complex auxetic behavior can also be studied using a modeling and simulation software. Identifying suitable manufacturing processes, such as knitting, weaving, bonding and (or) 3D printing to optimize the structures created in this study could constitute an entire study by itself.

The scale of the current prototypes is macroscopic (it is visible to the naked eye). Although Poisson’s ratio is a scale-independent property, for the intended impact protective clothing application, a minimum of 10cm by 10cm dimension is recommended. Factors influencing the effectiveness of these mechanisms at a particular scale would be the nature of the material used (including base material and fasteners/accessories as appropriate to the structure) and manufacturing process.

Throughout this study, focus has been given to auxetic materials that respond by growing along the Z-direction when subjected to a tensile or shear force along the Y direction. These can be considered as *passive* smart materials (Fairweather, J.A., 1998), since these are not capable of converting one form of energy to a different form. The stimulus and response for these materials are mechanical in nature. Further, these materials are designed to react only at the time of impact. However, in contrast to this, an *active* smart auxetic could offer ‘pre-collision avoidance,’ a feature that is often built into modern cars these days. An active smart auxetic system would dynamically trigger the auxetic mechanism, when it senses that there is an object in the vicinity that can potentially cause impact injury. The stimulus is electrical (signal) and the response is mechanical (auxetic action).

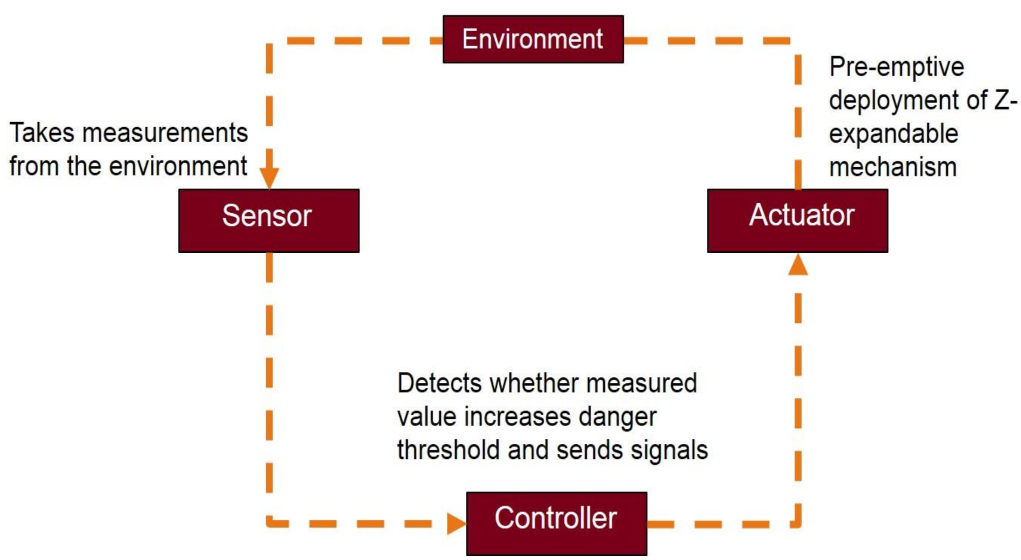


Figure 73: Active smart Z-Expandable Auxetic

An active smart Z-expandable auxetic may consist of

i) Sensors that continuously monitor and take measurements from the environment (examples include velocity, position and size of objects that could potentially cause an impact injury). It could also consist of sensors for fall detection that monitor the motion of the wearer.

ii) A controller that detects whether or not the measured value exceeds the danger threshold and sends a signal to activate the actuator accordingly. Taking this one step further, the controller could perhaps also decide on the extent to which the the auxetic material should grow along the Z-direction, perhaps depending upon the dimensions of the obstacle.

   Also, in case the wearer's motion is perceived as a 'fall,' the controller could then send a signal to the actuator to activate the auxetic mechanism.

iii) An actuator that preemtively deploys the Z-expandable auxetic mechanism, in order to minimize foreseeable injury from impact.

Such a Z-expandable auxetic with control systems (Figure 73) could find applications in adventure sports. These could be used in helmets for motorcyclists, to lessen the severity of impact from collisions to the head, and perhaps even in spacesuits to minimize micrometeoroid impact. It could also be used in baby pants with a fall detector, to activate the mechanism prior to falling on their knees. Thus, the future and growth potential for Z-expandable auxetic applications is both promising and high.

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Appendix

Instron Quick Start Guide for Stretch Test

- TURN ON INSTRON (make sure that windows is ON and fully loaded)
- From INSTRON Transducers box wait that the displayed number count down to 2 (or less)
- Open Merlin (Software)
- Click on the desired method (if you want to initiate a new method, you can still open and existing one and then create new method after it is fully loaded)
- Wait for firmware to load (there are to firmware indicator that automatically show up one after the other, and should both load up to 100%. If this does not happen, turn OFF INSTRON and start the process from the beginning. If INSTRON keeps not responding, and reboot of the windows machine is needed)
- After firmware is fully loaded, INSTRON responds to JOG UP – JOG DOWN commands. Set clamps distance at the desired position, clamp the fabric you want to stretch
- After that method is loaded (or new method created), open Test Control (stop light icon) to manually setup your test
- From Test Control, Motion windows: select Ctrl. Mode: Extension; desired speed (2.5in/min is my default); Direction at Start UP. (NOTE: the Sensitivity would need to be checked with the corresponding action, for example Stop, for a breaking test)
- From Test Control, Events window: un-check all options (NO EVENTs)
- From Test Control, Cycling windows: un-check ‘Enabled first’; select maximum X.XX inch extension value (NOTE: the inch value set in INSTRON is scaled by a factor ~5. To get an approximation of the true extension multiply the X.XX set value by 5: X.XX*5 = approximation of true extension); select number of cycles and Return action, after each cycle; Check both Enabled, form Extension and Cycles;
- Zeros extension values (‘Reset Gauge Length’)
- Start Test* **
- After test is completed, Click on End Sample, name the file, click OK
- The RAW data (*filename.raw*) are saved into the directory: C:\INSTRON\USER\DATA
- IMPORT *filename.raw* into excel format: Open excel; Open *filename.raw* and then IMPORT it as a comma separated file; SAVE AS Excel Workbook (*.xlsx)
- Start a new Test
- TURN OFF INSTRON: save method from File option in the bar tool; Exit from the File option in the bar tool.

*To calibrate INSTRON before starting test click on Calibrate icon. After Calibration is completed click on Done to return to main window and start the test. NOTE: calibration is not required before each test, if you already have a saved one for the same testing conditions.

**If clamps move too fast, or clamps come into contact, or something else happen, INSTRON frame is disabled (FRAME STANDBY indicator on INSTRON). To re-enable INSTRON frame click on INSTRON Icon by the displays, then click on Enable Frame. After that the Frame is re-enabled (FRAME READY indicator on INSTRON) click on Done to return to the main window.